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l. geol. Soc. Norfolk, 32, 1-35 (September 1982)

TERNARY SEDIMENTATION IN THE SIZEWELL-DUNWICH BANKS AREA, SUFFOLK

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bara J. Lees*

mary

Evidence from geophysical surveying, grab sampling, box and vibrocoring has n used to deduce the sedimentation sequence and an outline of the Quaternary tory of the Sizewell-Dunwich area, off the Suffolk coast. The present sedimentary ime is the result of one or more periods of marine transgression of an estuarine ayment during the Holocene epoch, together with erosion of the nearby cliffs of onsolidated Pleistocene sediments. The interaction between tidal dynamics and erosion processes has given rise to the present day linear sandbank lying allel to the coast.

Introduction

During the course of a field investigation of the large scale processes of iment transport in the Sizewell-Dunwich Banks area, off the East Anglian coast g 1), data have been collected which are relevant to the understanding of the ternary history of the region. This paper summarises the evidence and shows t the present sedimentary regime is the result of one or more periods of marine nsgression of a broad coastal estuary during the Holocene epoch, coupled with sion of the unconsolidated Pleistocene sediments of the adjacent coastline. interaction between the coastal erosion and tidal processes has resulted in formation of the present-day linear sandbank, lying parallel to the shoreline.

Although many workers have studied the coastal geology of Suffolk, including d (1882), Wood (1886) and Harmer (1900) in the early days, (cited in Funnell West (1977)), to Hey (1967), West and Norton (1974) and West, Funnell and ton (1980) more recently, little has been undertaken offshore. The bedrock logy is currently being mapped by the Marine Geophysics Unit of the Institute

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stitute of Oceanographic Sciences, Crossway, Taunton, Somerset, TA1 2DW.

of Geological Sciences and Millner et al (1977) have carried out geophysical surveys in the area. The 1957/8 site surveys prior to the construction of the Sizewell Nuclear Power Station (Fig 1) included boreholes onshore and immediately offshore of the site (Gammon and Pedgrift, 1962). The borehole samples were made available to West and Norton (1974) and they note that although recognisable Pleistocene sediments are present, the subdivision of the sequence is made difficu by the general similarity of the lithology throughout and by the lack of diagnosti palaeontological data. The sediment distribution on the seafloor adjacent to the power station has been mapped by Bamber and Coughlan (1980).

Carr (1979) has shown that the rates of coastal erosion over time have been highly variable, ranging from zero to over 18 m y^{-1}, although there appears to have been some synchroneity in peaks of erosion overall. Offshore, hydrograph charts covering the period 1824-1965 demonstrate the growth of the Sizewell Bank to the N, and the progression shorewards of the bank system.

2. Coastal Geology

The coastline in the study area curves inland very gently from a slight ness at Southwold in the N to a similar, but more prominent, feature at Thorpeness in the S (Fig 1). A small river, the Blyth, flows into the sea immediately S of Southwold.

The term Crag is one used locally for any shelly sand (Chatwin, 1961). The Pliocene representative is the Coralline Crag, outcropping in the S near Aldeburgh and almost certainly continuing for a short distance offshore as the core of Thorpe Ness. The samples examined from this area comprise shelly sands and bryozoan fragments, with secondary iron-staining. Further N the character of the Crag changes to beds of sand, laminated clays and pebbly gravels, with varying amounts of iron-staining, lying unconformably against the Coralline Crag. These deposits are known as the Norwich Crag Series and are of preglacial Pleistocene age (Funnell and West, 1977). The Westleton Beds form a gravel

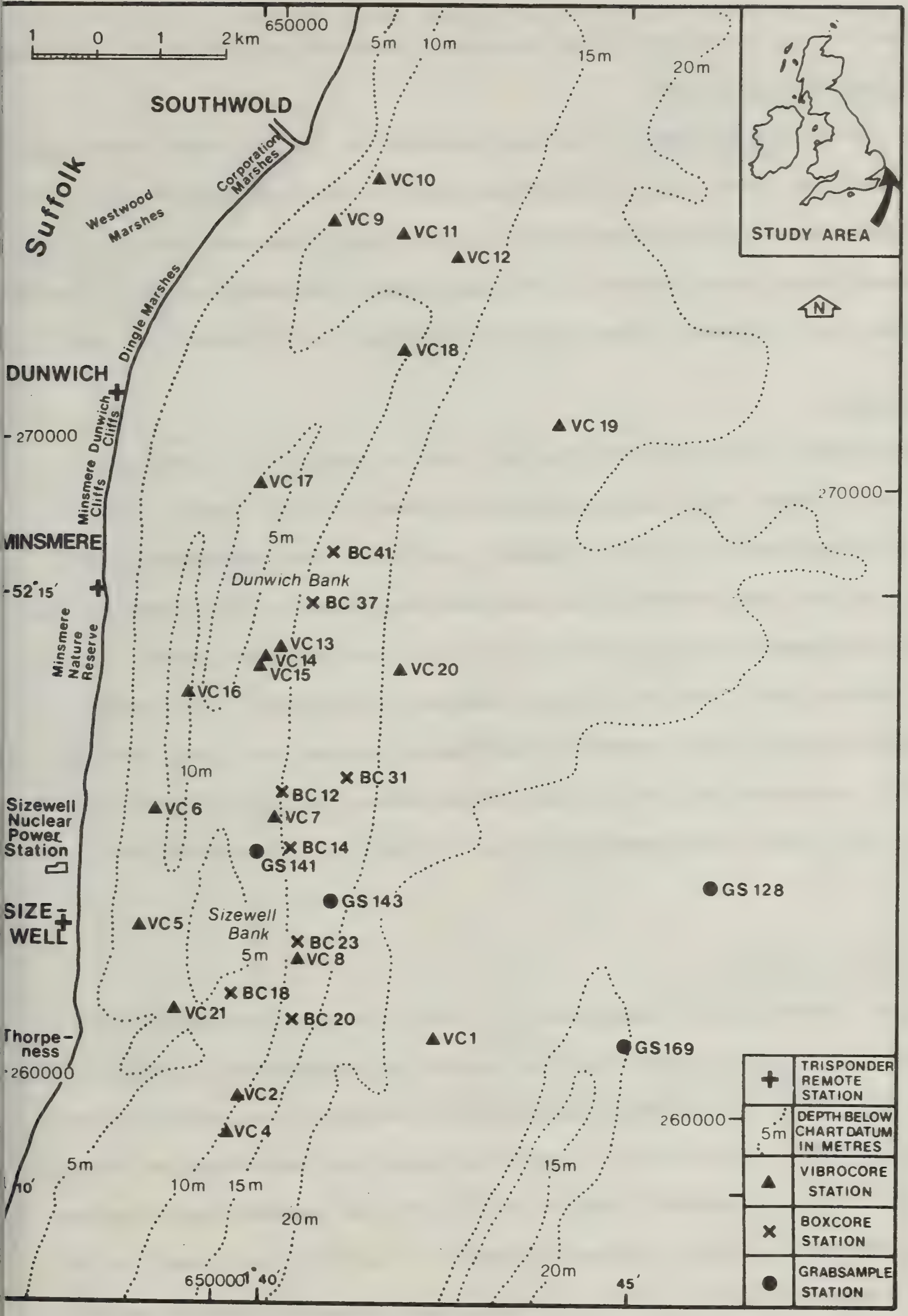
1 0 1 2 km
650000
SOUTHWOLD
Suffolk
Westwood Marshes
Corporation Marshes
Dingle Marshes
DUNWICH
Dunwich Cliffs
Minsmere Cliffs
MINSMERE
Minsmere Nature Reserve
Sizewell Nuclear Power Station
SIZEWELL
Thorpeness
270000
52°15′
260000
10′
5m
10m
15m
20m
VC10
VC 9
VC 11
VC 12
VC18
VC 19
VC 17
BC 41
Dunwich Bank
BC 37
VC13
VC14
VC15
VC 16
VC 20
BC 31
BC 12
VC 6
VC 7
BC 14
GS 141
GS 143
GS 128
Sizewell Bank
VC 5
BC 23
VC 8
BC 18
VC 21
BC 20
VC 1
GS 169
VC 2
VC 4
650000
1°40′
45′
STUDY AREA
N
TRISPONDER REMOTE STATION
DEPTH BELOW CHART DATUM IN METRES
VIBROCORE STATION
BOXCORE STATION
GRABSAMPLE STATION

Fig.1

Location map of Sizewell-Dunwich Banks showing vibrocore stations, also grab sample and box core stations mentioned in text.

horizon at the top of the series and are seen at Dunwich, comprising the uppermost 2-3 m of the 20 m high cliff.

The last geological maps of the area published by the Geological Survey were in 1886 (southern sheet) and 1887 (northern sheet). The distribution of alluvial clay shown in Fig 2 is taken from these maps, and apart from some erosion at the shoreward side is not expected to be significantly different today. The areas of Pliocene and Pleistocene Crags are taken from Fig 18.1 of Funnell and West (1977).

3. Procedures

The earliest field data were obtained during a geophysical survey using "boomer" and "pinger" and a grab sampling programme, with 251 samples. Both surveys were carried out in 1975. Figures 3 and 4 show the geophysical survey trackplot and the area covered by the grab sampling respectively. These initial data were supplemented during 1978 and 1979 when a grab was used during various surveys forming part of bedload sediment transport experiments. As a result it was possible to show limited sediment distribution changes over time. Further geological information was obtained from 58 box cores, taken in 1975, 1977, 1978 and 1979, and also 20 vibrocores drilled in 1978 and 1979 at selected sites (Fig 1).

4. Offshore Topography

Figure 2 shows that offshore there is a gently sloping platform reaching a mean depth of 15 m below Chart Datum (1.4 m below OD) approximately 4 km offshore. Lying on this platform is a linear sandbank with its long axis parallel to the coastline and about 2 km from it. There is a central col separating the Dunwich Bank to the N from the Sizewell Bank to the S. The two together are 11 km long and approximately 1 km wide, with mean slopes of 1 in 60 to the W, and 1 in 200 to the E. Inshore from the bank is a trough, again elongated parallel to the shoreline, and reaching a mean depth of just over 9 m below Chart Datum.

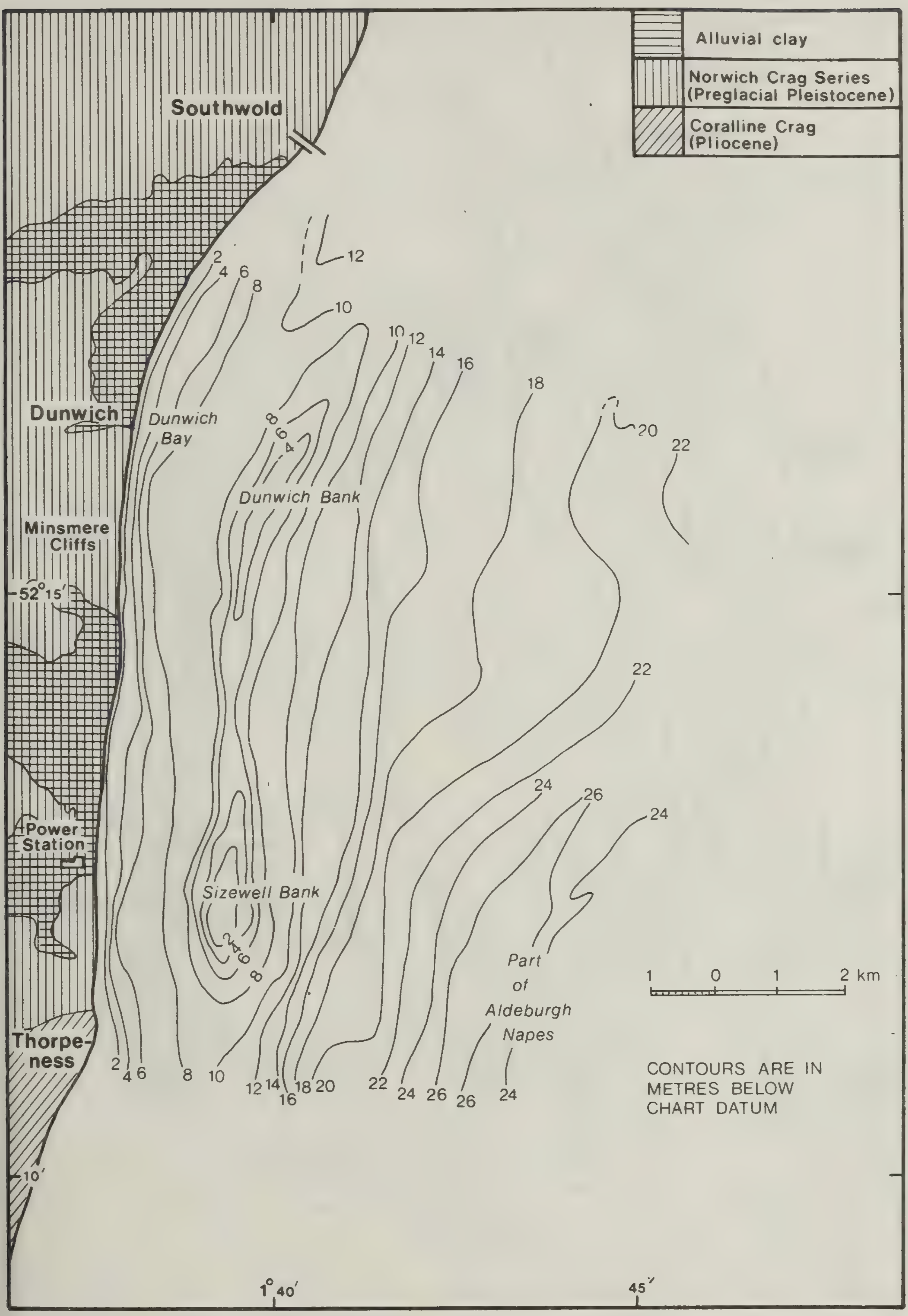
Alluvial clay
Norwich Crag Series (Preglacial Pleistocene)
Coralline Crag (Pliocene)
Southwold
Dunwich
Dunwich Bay
Dunwich Bank
Minsmere Cliffs
52°15′
Power Station
Sizewell Bank
Thorpeness
10′
1°40′
45′
Part of Aldeburgh Napes
1 0 1 2 km
CONTOURS ARE IN METRES BELOW CHART DATUM
2 4 6 8 10 12 14 16 18 20 22 24 26

Fig. 2

Coastal geology, taken from maps of the area published by the Geological Survey, and Fig. 18.1 of Funnel and West (1977) and bathymetry deduced from a partial Hydrographic Office survey (2 N-S lines, 8 E-W lines), August 1976. (Produced from a portion of BA Survey No. K4799 with the sanction of the Controller, HM Stationery Office and of the Hydrographer of the Navy).

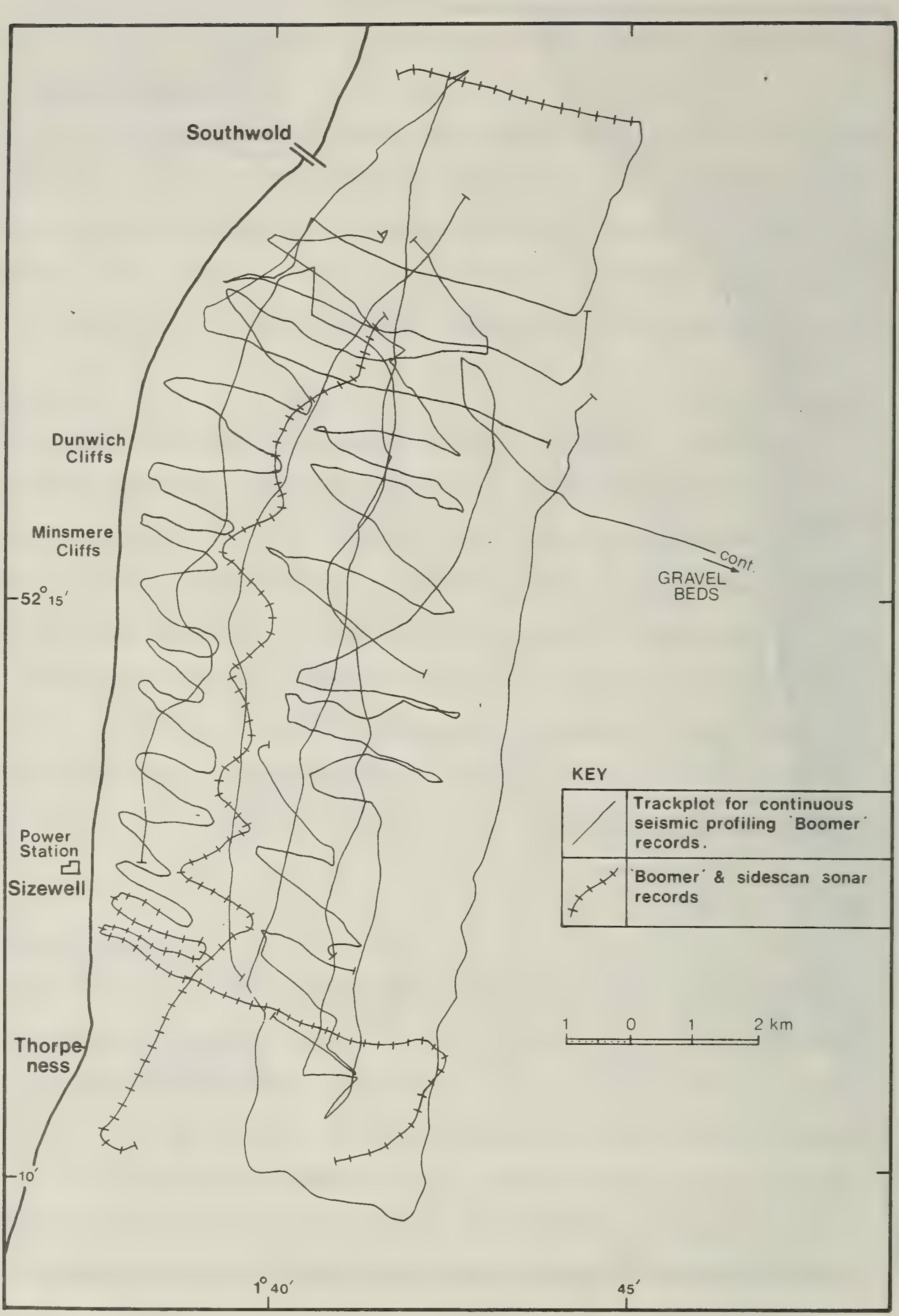
Southwold
Dunwich Cliffs
Minsmere Cliffs
52° 15′
Power Station
Sizewell
Thorpeness
10′
1° 40′
45′
cont.
GRAVEL BEDS
KEY
Trackplot for continuous seismic profiling 'Boomer' records.
'Boomer' & sidescan sonar records
1 0 1 2 km

Fig. 3

1975 trackplot for continuous seismic profiling and sidescan sonar surveys

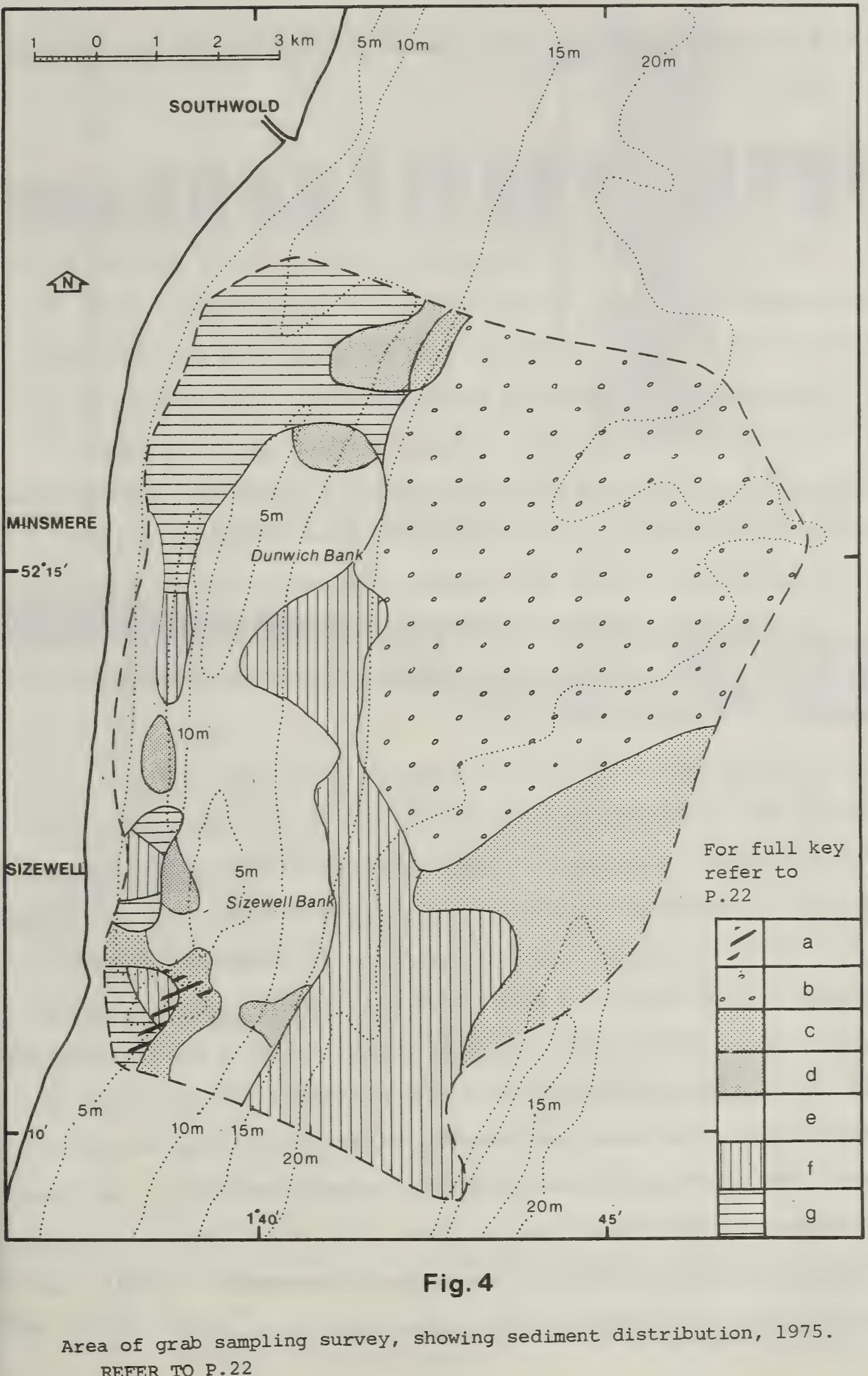
1 0 1 2 3 km
SOUTHWOLD
N
MINSMERE
52°15'
SIZEWELL
10'
1°40'
45'
5m
10m
15m
20m
Dunwich Bank
Sizewell Bank
For full key refer to P.22
a
b
c
d
e
f
g

Fig. 4

Area of grab sampling survey, showing sediment distribution, 1975.
REFER TO P.22

A 6 m to 8 m deep channel exists between Thorpe Ness and the southern end of the Sizewell Bank.

5. Geophysics

There was no significant reflection from, or acoustic penetration of, the bedrock. Although isolated reflectors can be detected, none of them continues for any substantial distance. The best example is shown in Fig 5A, where the superficial sediments are only a few cm thick and a series of good reflectors at 0.25 m intervals can be identified in the bedrock.

Above the bedrock the character of the reflections from the acoustic horizons and the amount of penetration have enabled 4 stratigraphic units to be designated. The first, Unit 1, lies immediately above the bedrock and is thickest, up to perhaps 15 m, in the nearshore area off Dunwich and Walberswick (Fig 1). It appears to thin to both the N and S. Very little internal structure is shown, and over most of the area it is not possible to detect the base, hence the thickness is an estimate only.

The remaining three units are all exposed at the surface. The most important is that comprising the banks, Unit 2, and its thickness can be mapped with some confidence, particularly in the northern part of the area. Figure 6 is the resulting isopachyte map, and a maximum thickness of over 9 m is demonstrated in the area of the Dunwich Bank. Seismic profiling traverses of the Dunwich Bank, clearly showing the base of Unit 2, are shown in Fig 7A and B.

Unit 3 has a relatively poor reflecting surface. There is acoustic penetration, but many irregularities are shown. The strata are found adjoining Unit 2, on the eastern flank of the banks, and there may be gradation between the two in some areas. The fourth unit shows virtually no acoustic penetration, and therefore no estimate of its thickness can be given. This lack of penetration enables the boundary between Unit 4 and Unit 2 to be clearly designated (Fig 5B). Unit 4 occurs along the eastern boundary of the study area.

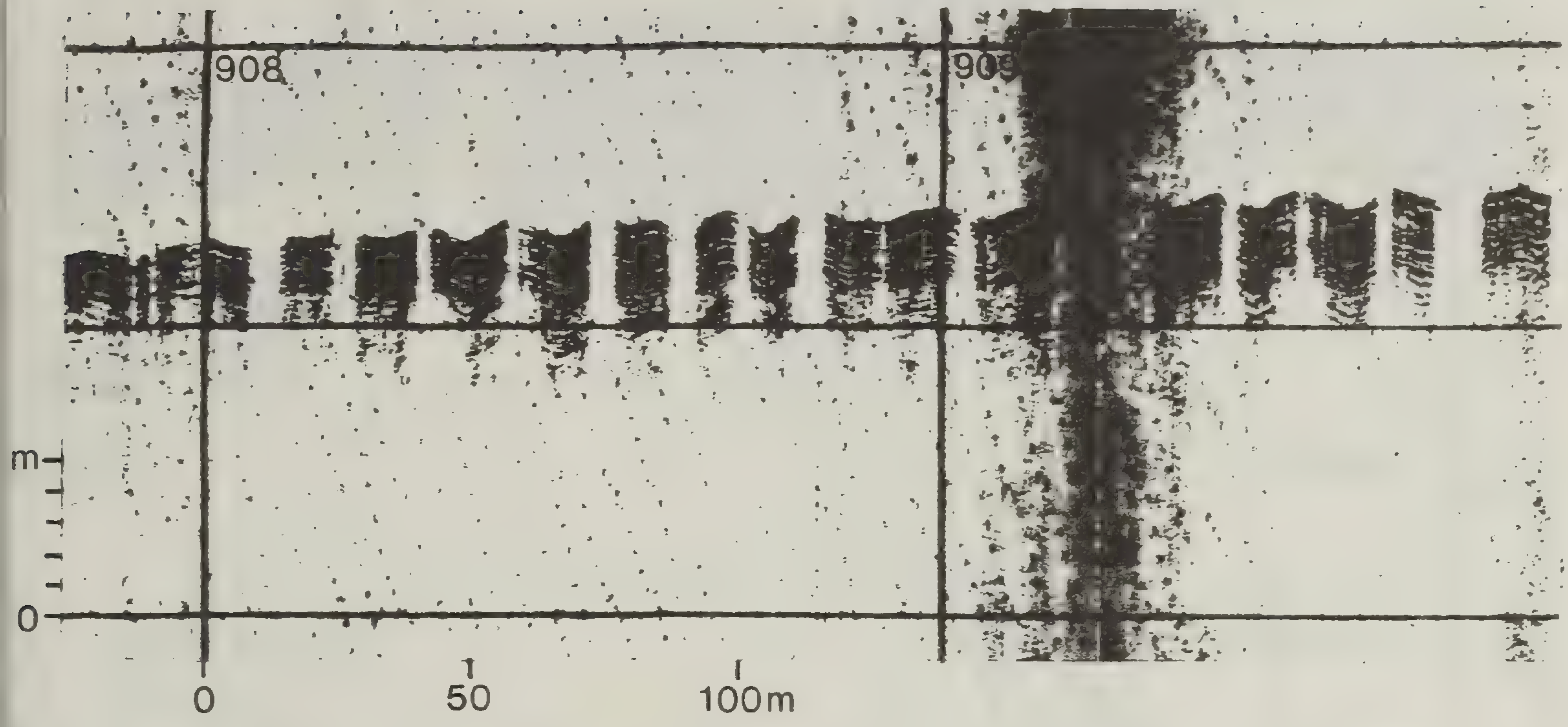

Fig. 5 A Part of seismic profiling record showing reflections from alternating layers of sand and clay of Norwich Crag Series

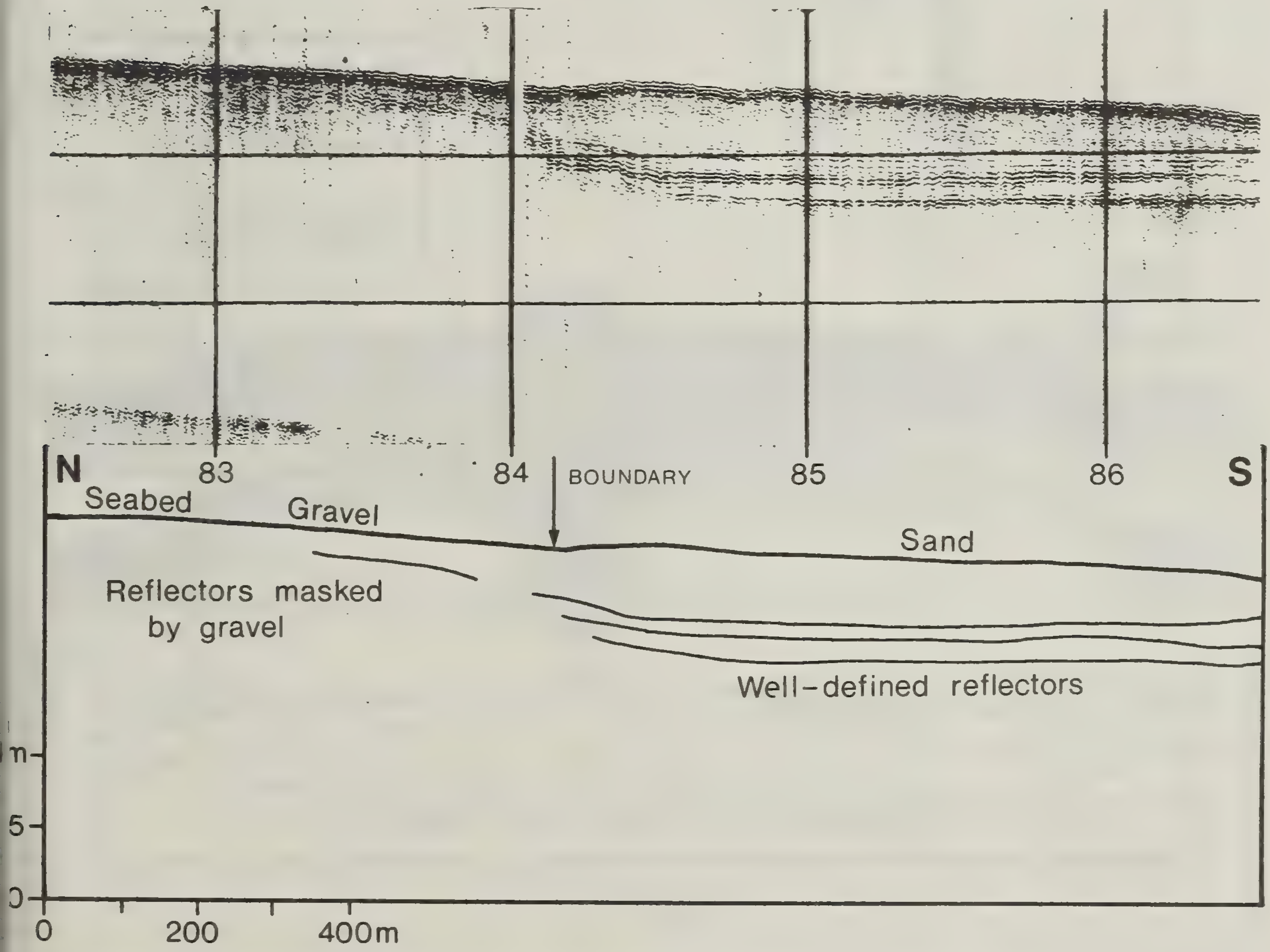
N
83
84
BOUNDARY
85
86
S
Seabed
Gravel
Sand
Reflectors masked by gravel
Well-defined reflectors
m
5
0
0
200
400m

Fig. 5 B Seismic profiling traverse showing boundary between gravel and sand on seabed surface

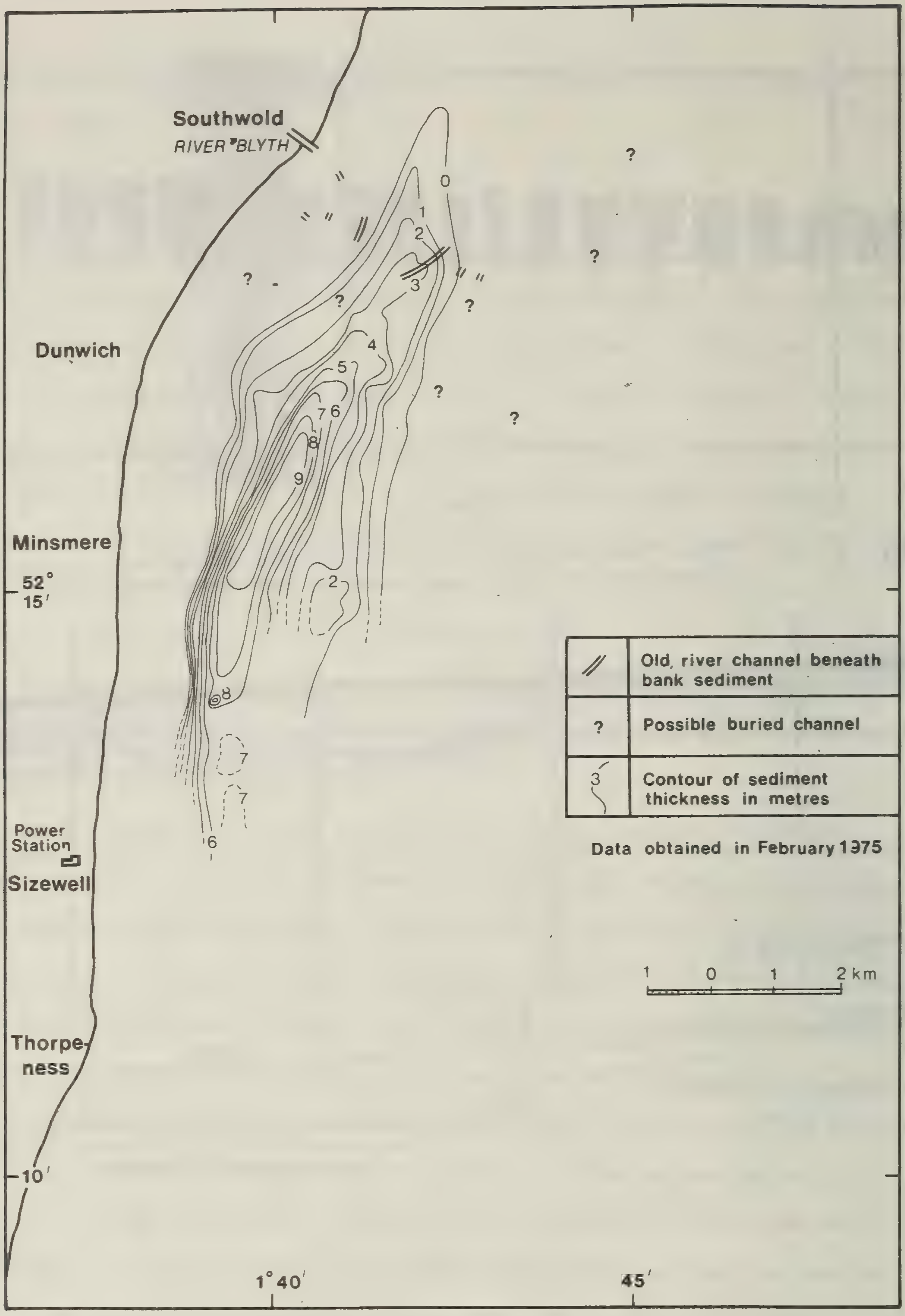
Southwold
RIVER BLYTH
Dunwich
Minsmere
52°
15′
Power Station
Sizewell
Thorpeness
10′
1°40′
45′
0
1
2
3
4
5
6
7
8
9
2
8
7
7
6
?
Old, river channel beneath bank sediment
Possible buried channel
Contour of sediment thickness in metres
Data obtained in February 1975
1 0 1 2 km

Fig 6

Isopachyte map of sediments forming Sizewell-Dunwich Banks, also showing locations of possible buried channels.

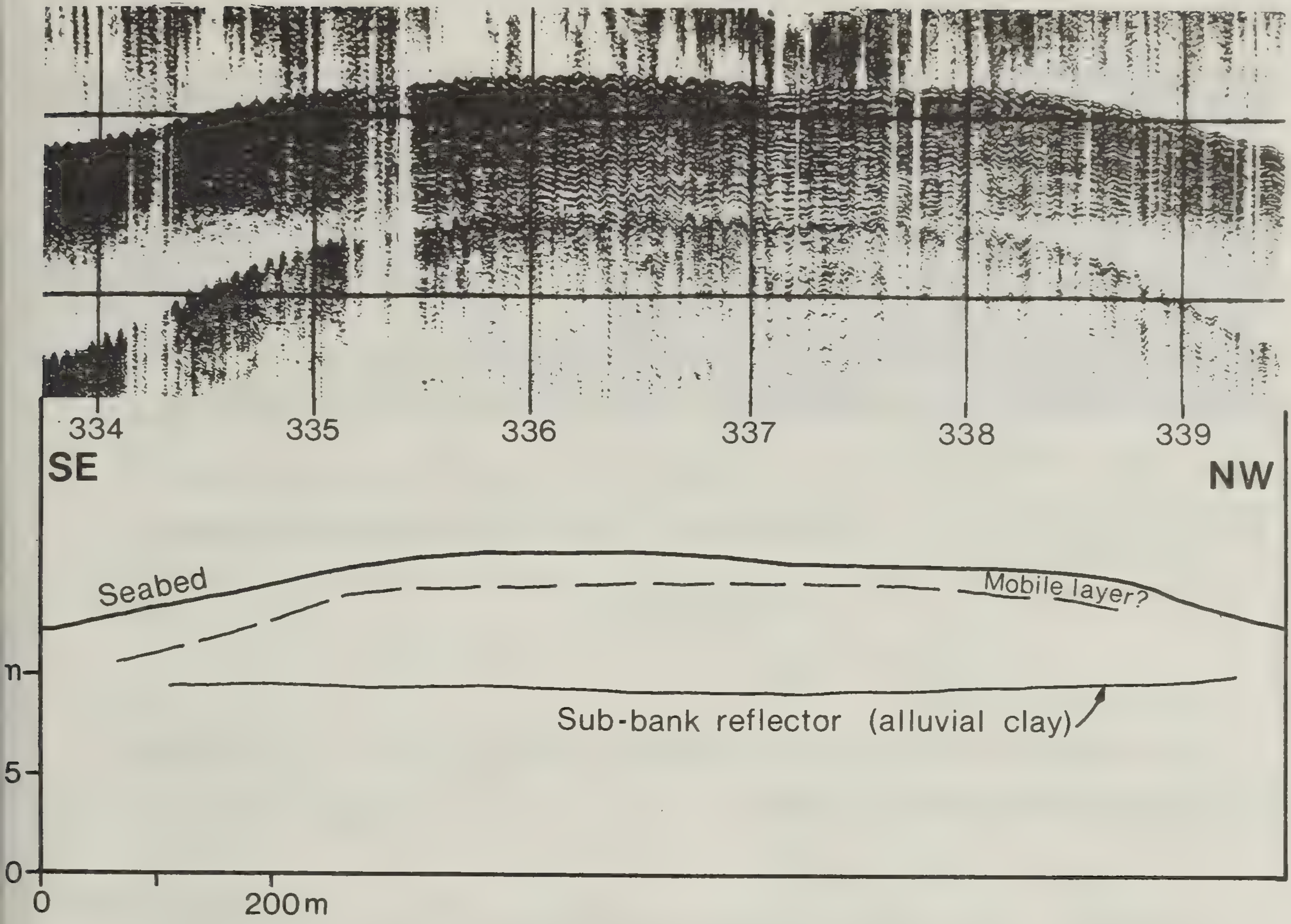

Fig. 7 A

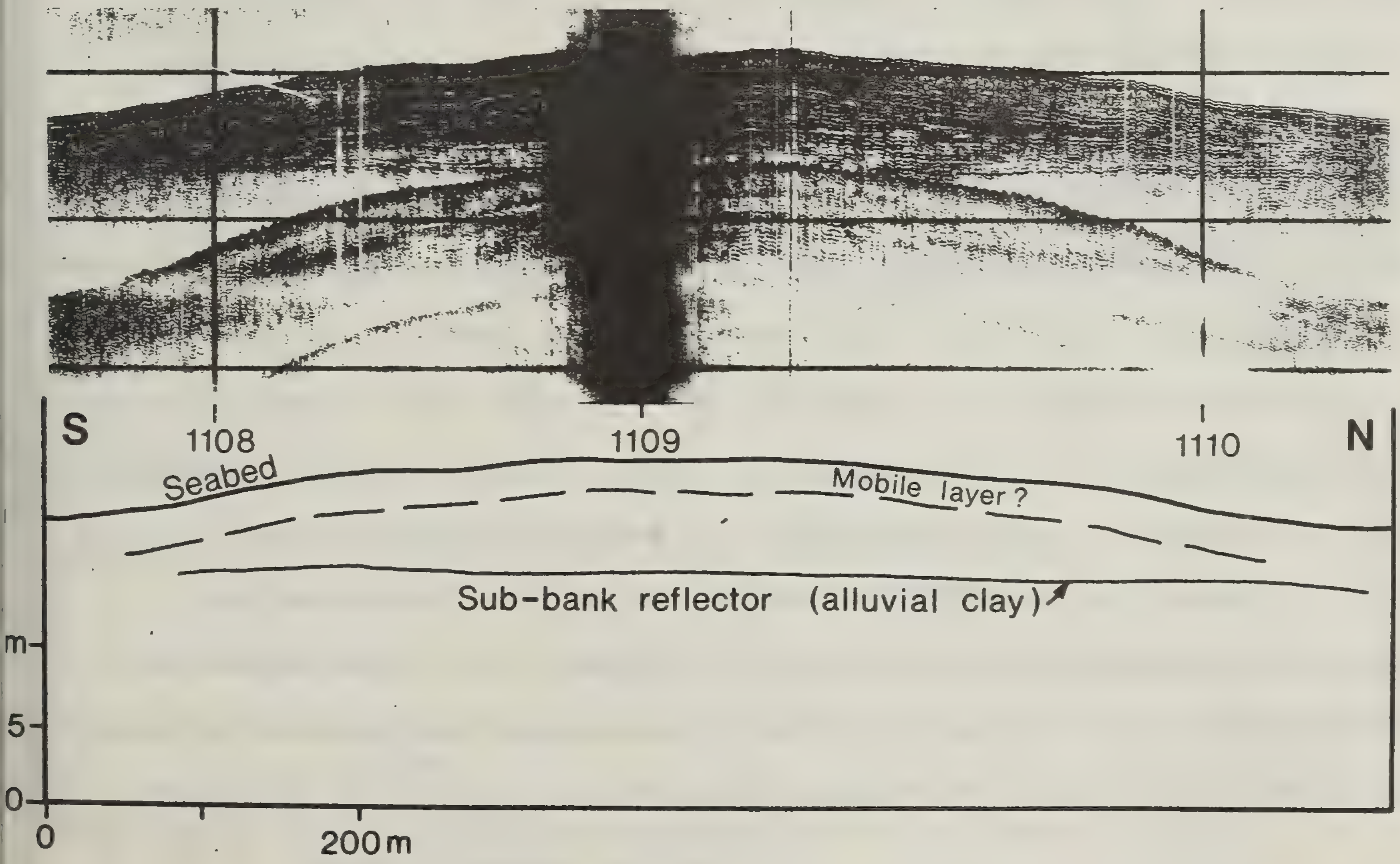

Fig. 7 B

Figs 7A and B Seismic profiling traverses of SW part of Dunwich Bank showing sediments lying on alluvial clay, with probable mobile layer at surface

A feature of importance detected by the seismic profiling is the presence of buried channels to the SE of Southwold (Fig 6). The areas where the evidence is of poorer quality are indicated by query marks, and the number of channels detected or suspected shows that the distribution pattern is complex. The channels cannot all be attributed to one river, but are more likely to be the remains of the tidal channels of an estuary. They are found beneath Unit 2, and either in or below Unit 1. Examples of two traverses in different directions through a buried channel are shown in Fig 8A and B. The covering sediments are seen to be approximately 3 m thick at this site.

6. Stratigraphic Units

The sediments present have been grouped as shown in Table 1 on the bases of lithology and macrofossil content.

6.1 Pliocene Coralline Crag

The deposits identified as Coralline Crag comprise medium grade, iron-stained sands with comminuted and fragmented shell, and show occasional silty clay laminae. Their colour is bright ochre-yellow. They are restricted to the SW of the area, and are in the form of an ENE-WSW aligned ridge, almost certainly an offshore continuation of the Coralline Crag forming the core of Thorpe Ness. Rock exposures with an ENE-WSW strike have been detected by sidescan sonar on the seafloor near Thorpe Ness, and are probably Crag *in situ*. The ridge has a thin cover of less than 1 m of sediments which gradually thickens to over 1 m to the ENE (Cores VC 21, 8, Fig 10D, 10B, 11). The rock is identified as upper Coralline Crag from its macrofossil content (R Markham, personal communication and the species are listed in Appendix 1. A schematic section is shown in Fig 9.

The sands lying immediately above the Crag are also iron-stained and apparently derived from it. Where they are exposed at the seabed surface near Thorpe Ness they have spread in a strip of increasingly finer material following the shoreline N as far as the Minsmere Nature Reserve, but with a gap opposite

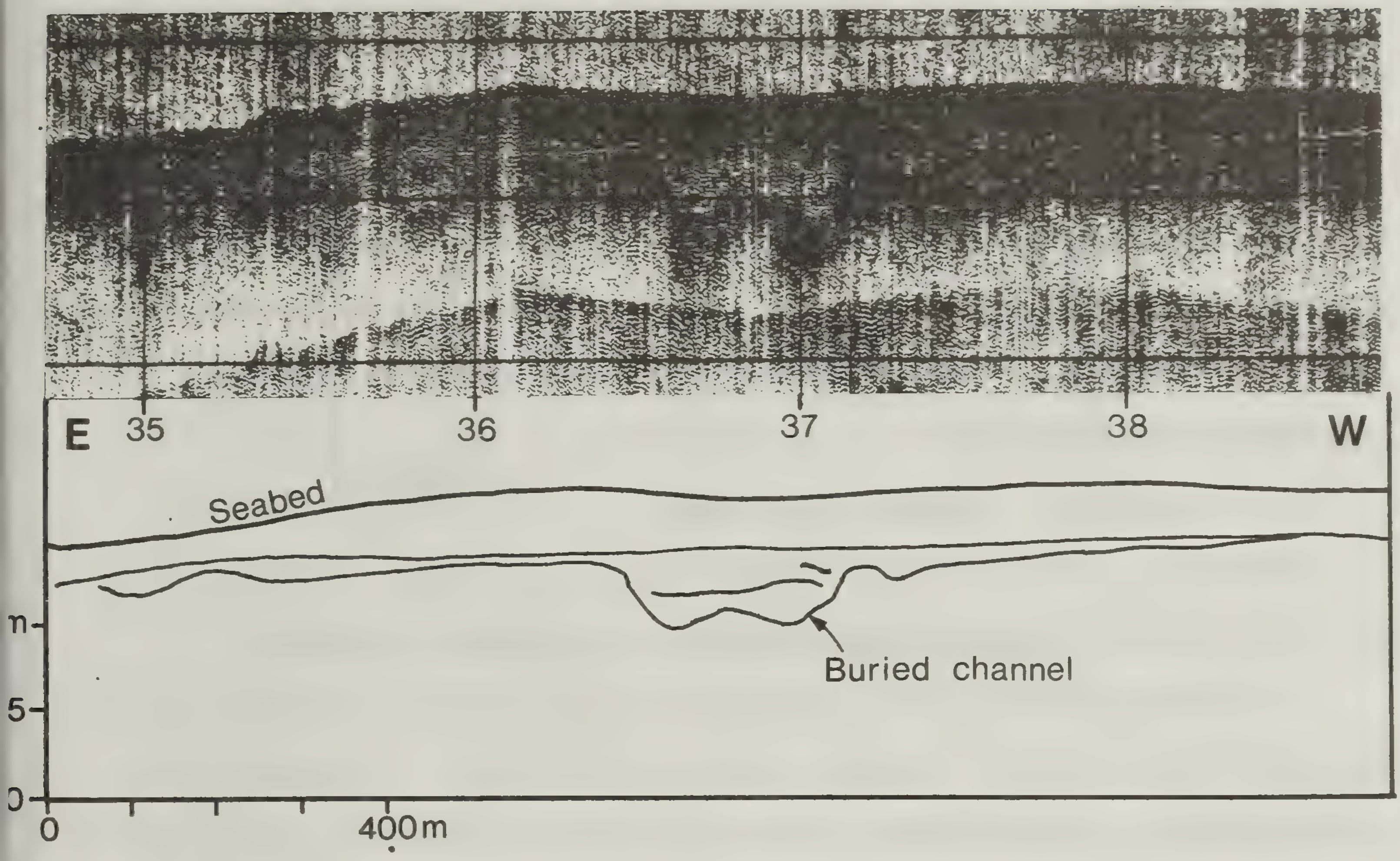

Fig. 8 A

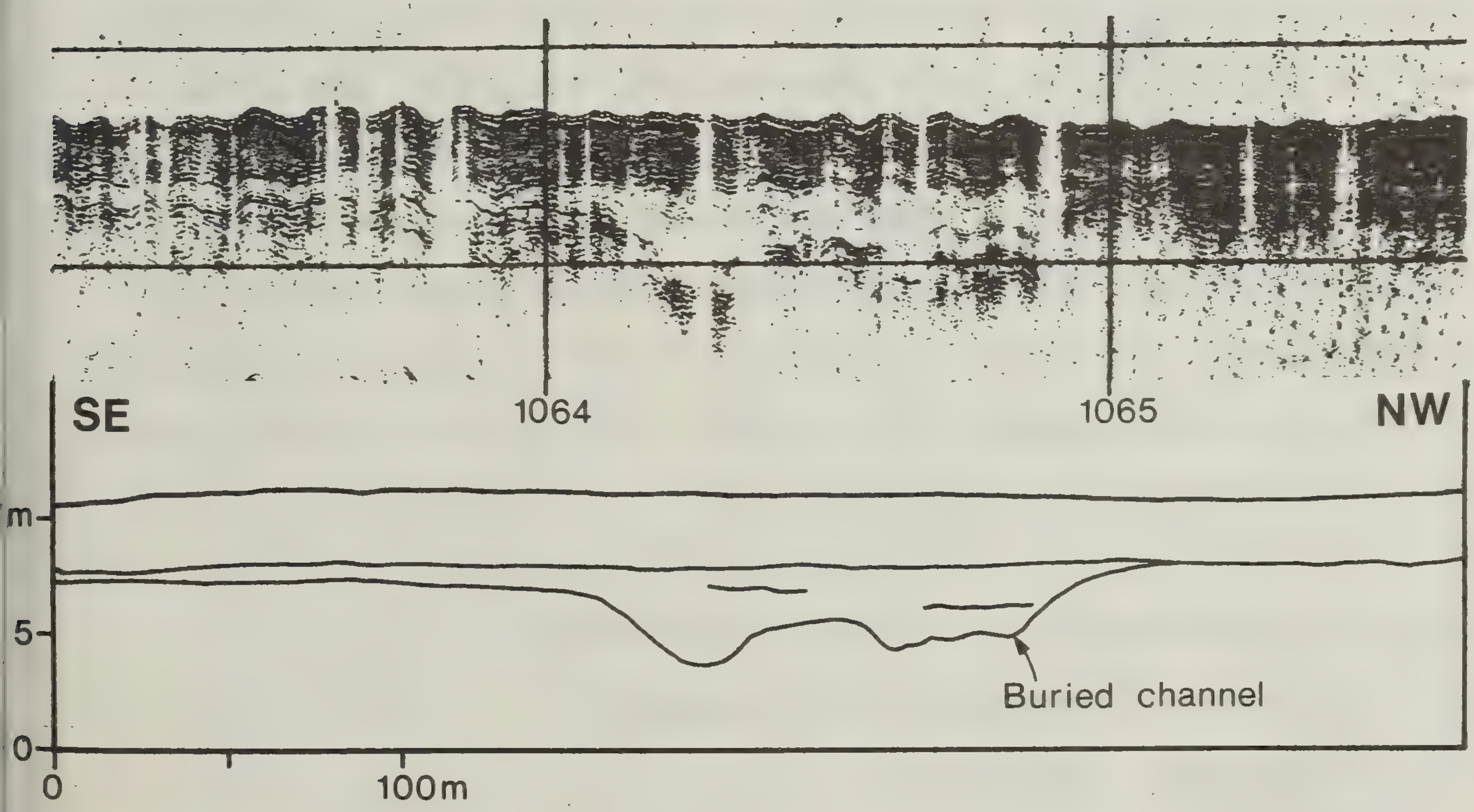

Fig. 8 B

Figs. 8A and B
Two traverses, E-W and SE-NW, of buried channel 2km SE of Southwold harbour entrance.

the Sizewell Power Station. Unfortunately the samples of these sands were discarded in the field, after assessing their mean grain size, so it is not clear whether those N of the power station have been mainly derived from the Coralline Crag, or the Norwich Crag Series of the cliffs. The mean grain size changes would be more consistent with the former origin, but the pattern of tidal current residuals in the area suggests a sediment transport path to the S (Heathershaw and Lees, 1980).

6.2 Pleistocene Norwich Crag Series

Subdivision of this series into members and beds (Funnell and West, 1977) has not been made due to the restricted nature of the evidence available.

The lithology varies from clay through to coarse sands, containing varying amounts of shell and shell fragments, granules and pebbles. In general, the sediments become coarser upwards and the finer ones tend also to occur nearer to the present shoreline (Fig 11 and 10A, B, C and D). Many of the sediments show laminated structure and some exhibit current bedding. The iron-staining gives a colour range from yellow through to reddish, with the redder ones found towards the NW of the area. The lithology of the Norwich Crag in VC20, where bands of sand and clay alternate at 0.25 m intervals, could explain the form of the seismic profile already noted and illustrated in Fig 5A. The Norwich Crag Series probably underlies the whole of the study area, except perhaps the extreme S, and its surface will have been formed by continual erosion of the coastline and marine planation. A possible time-scale for this event will be discussed below. It has been located in situ in two cores (VC1, 20, Figs 10A, 10D and 11), and in derived sediments in cores located over most of the area (VC5, 6, 7, 8, 16 and 18, Figs 10A, B, C, D and 11). The surface shows a slight overall dip to the E, but there is no information on the thickness of the Crag.

The diagnostic fossils are listed in Appendix 1.

6.3 Holocene Alluvial clay

The sediment can be correlated with Unit 1, mentioned above when describing

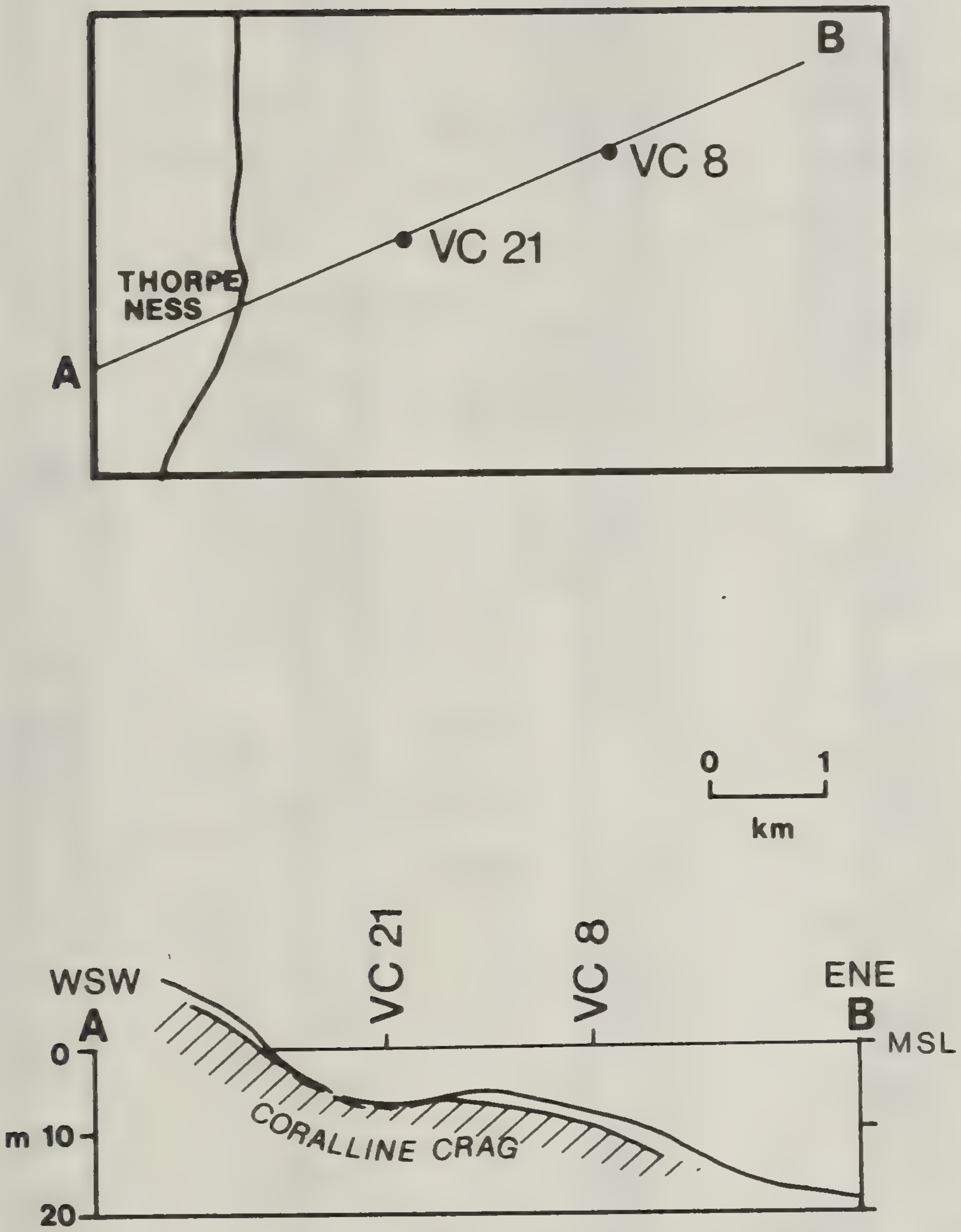
B
VC 8
VC 21
THORPE
NESS
A
0
1
km
VC 21
VC 8
WSW
A
ENE
B
MSL
0
m 10
20
CORALLINE CRAG

Fig 9 Schematic section of the Coralline Crag surface

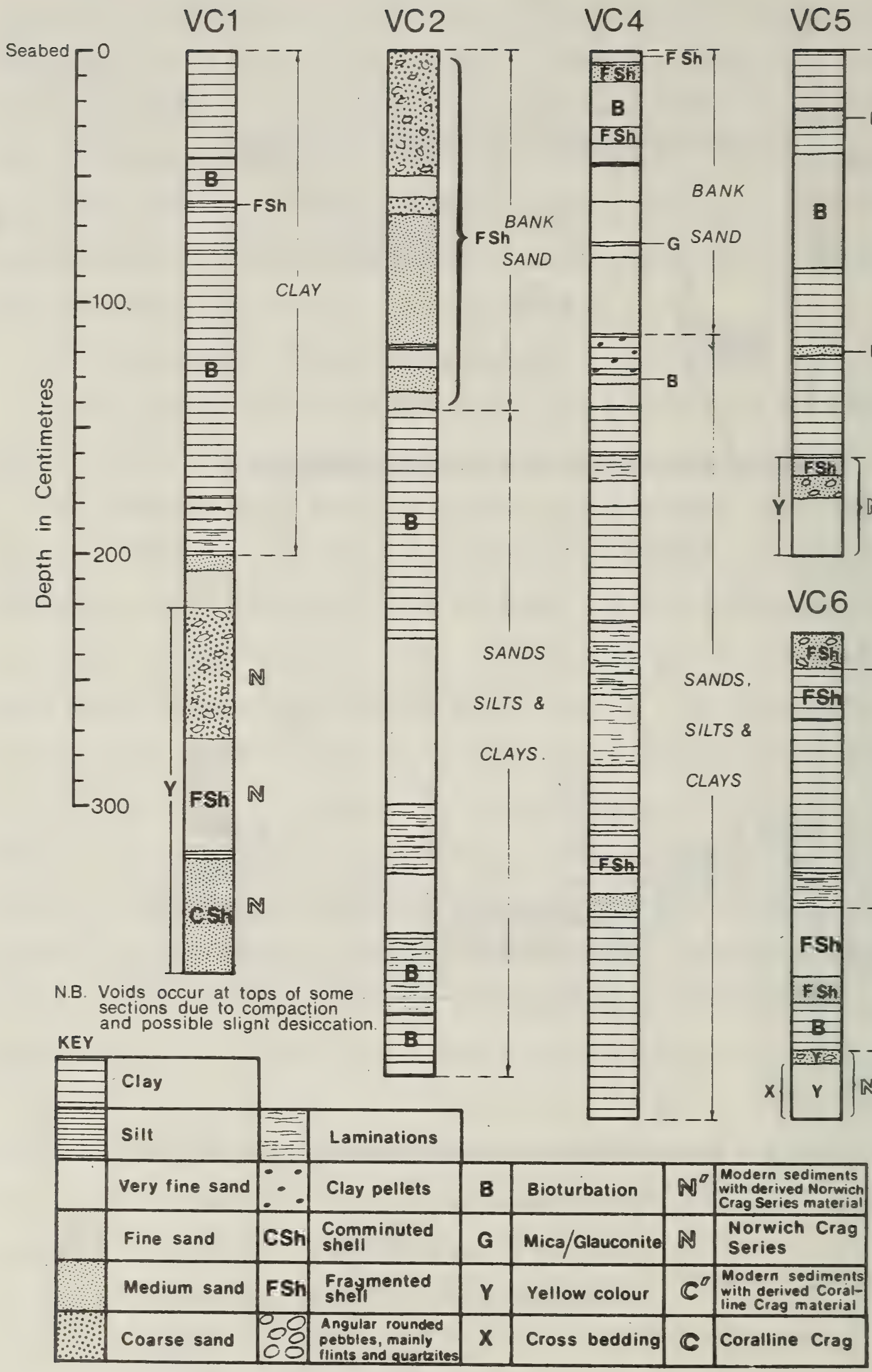
VC1
VC2
VC4
VC5
VC6
Seabed
0
100
200
300
Depth in Centimetres
B
FSh
CLAY
B
N
Y
FSh
N
CSh
N
BANK
SAND
FSh
SANDS
SILTS &
CLAYS.
B
B
B
F Sh
F Sh
B
FSh
G
BANK
SAND
B
SANDS.
SILTS &
CLAYS
FSh
FSh
B
SANDS.
SILTS &
CLAYS
FSh
FSh
Y
N°
FSh
FSh
BLUE -
GREY
CLAY
FSh
F Sh
B
Y
SANDS.
SILTS &
CLAYS
X
Y
N°
N.B. Voids occur at tops of some sections due to compaction and possible slight desiccation.
KEY
Clay
Silt
Very fine sand
Fine sand
Medium sand
Coarse sand
Laminations
Clay pellets
CSh Comminuted shell
FSh Fragmented shell
Angular rounded pebbles, mainly flints and quartzites
B Bioturbation
G Mica/Glauconite
Y Yellow colour
X Cross bedding
N° Modern sediments with derived Norwich Crag Series material
N Norwich Crag Series
C° Modern sediments with derived Coralline Crag material
C Coralline Crag

Fig. 10 A

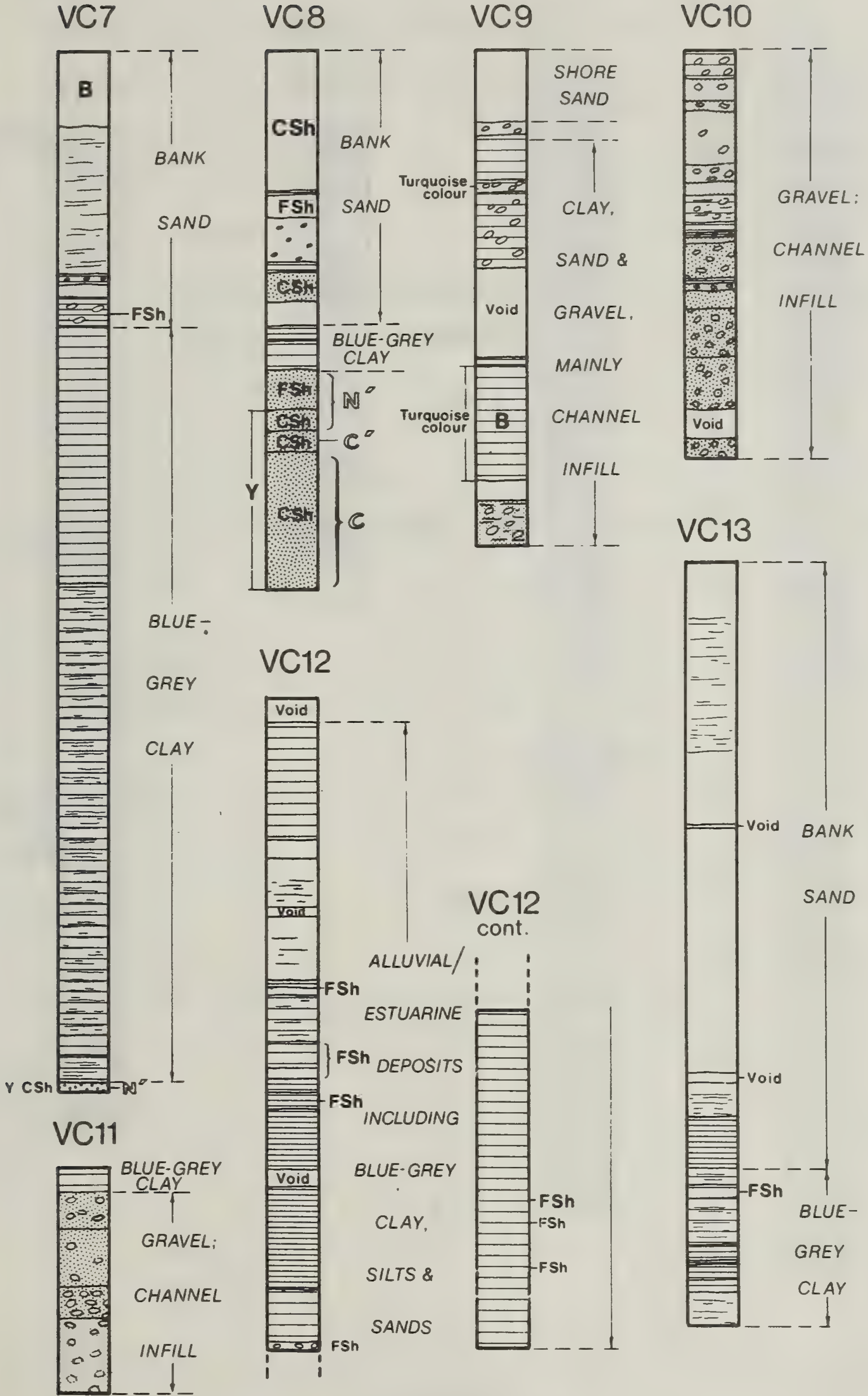
VC7
B
BANK
SAND
FSh
BLUE-
GREY
CLAY
Y CSh
N
VC8
CSh
FSh
CSh
BANK
SAND
BLUE-GREY
CLAY
FSh
CSh
CSh
N
C
Y
CSh
C
VC9
SHORE
SAND
Turquoise
colour
Void
Turquoise
colour
B
CLAY,
SAND &
GRAVEL,
MAINLY
CHANNEL
INFILL
VC10
Void
GRAVEL:
CHANNEL
INFILL
VC11
BLUE-GREY
CLAY
GRAVEL;
CHANNEL
INFILL
VC12
Void
Void
FSh
FSh
FSh
Void
FSh
ALLUVIAL/
ESTUARINE
DEPOSITS
INCLUDING
BLUE-GREY
CLAY,
SILTS &
SANDS
VC12
cont.
FSh
FSh
FSh
VC13
Void
Void
FSh
BANK
SAND
BLUE-
GREY
CLAY

Fig. 10 B

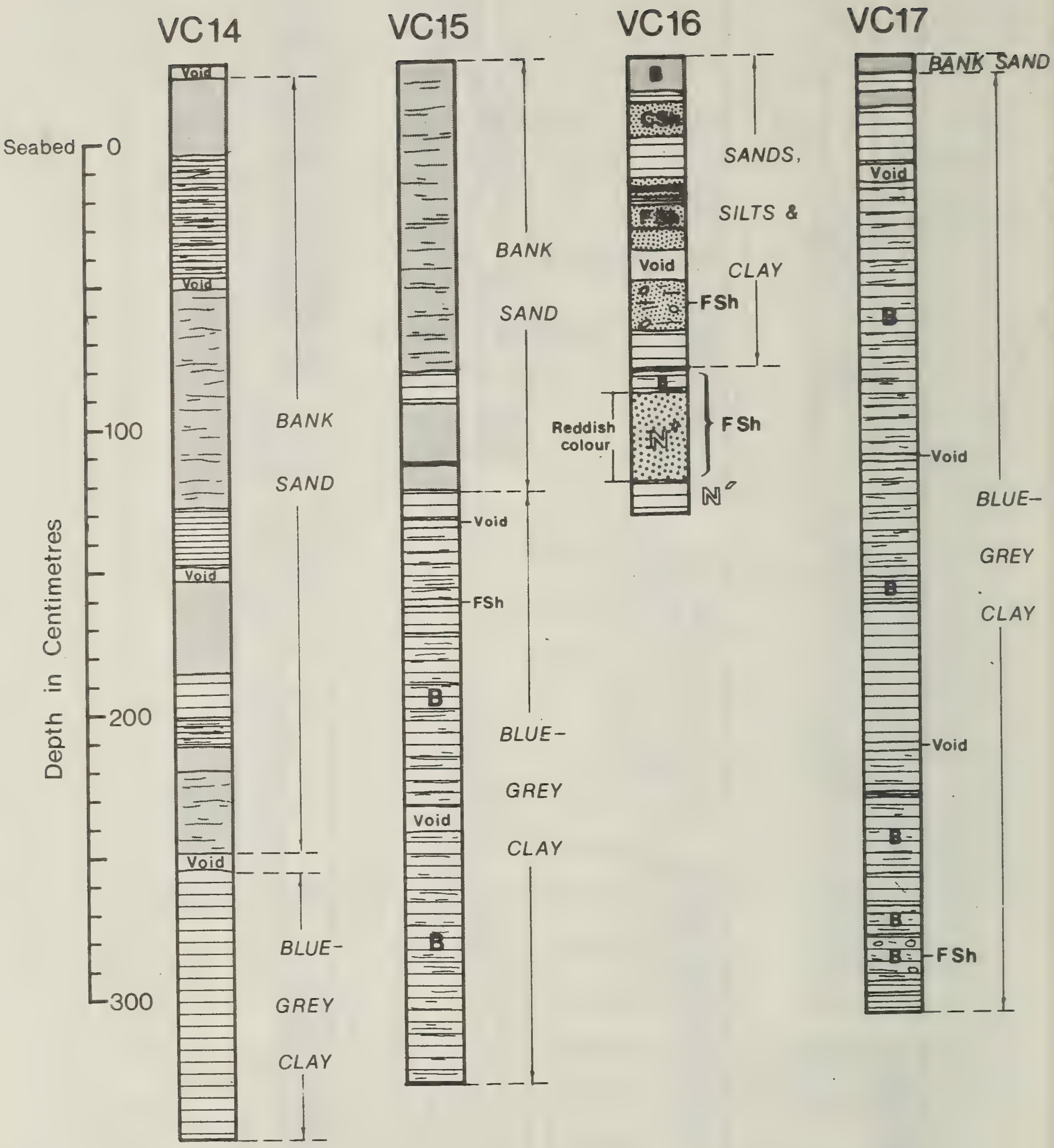
VC14
VC15
VC16
VC17
Seabed
0
100
200
300
Depth in Centimetres
Void
BANK
SAND
BLUE-
GREY
CLAY
FSh
B
SANDS,
SILTS &
CLAY
GSh
Reddish
colour
N
BANK SAND

Fig. 10 C

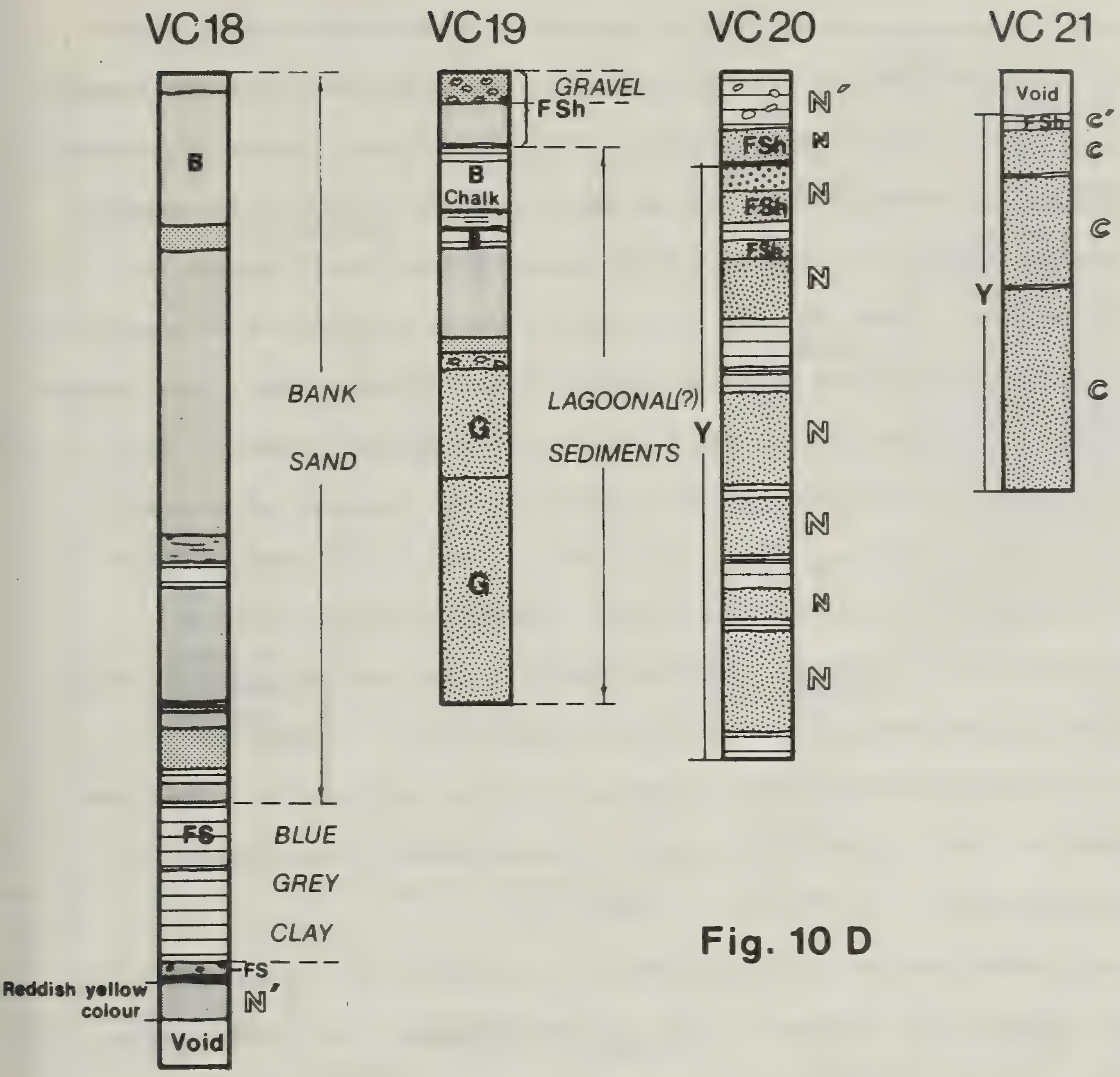
VC18
VC19
VC20
VC 21
B
BANK
SAND
FS
BLUE
GREY
CLAY
FS
Reddish yellow colour
N′
Void
GRAVEL
FSh
B
Chalk
B
G
G
LAGOONAL(?)
SEDIMENTS
N′
N
FSh
N
FSh
FSh
N
Y
N
N
N
N
Void
FSh
C′
C
C
Y
C

Fig. 10 D

Fig 10A to D Schematic longitudinal sections of vibrocores no 1-21 the seismic profiling results. It has a plastic consistency and contains lenses of silt and also black, oily patches, probably of organic origin. X-ray photographs show laminations, bioturbation and various shell remains. There is frequently a veneer of brownish sand and silt, only a few grains thick, which could be an artefact of sampling. When the tide is flowing there is always sand in suspension, which may settle out during the sampling process (Lees, 1980a). The colour changes from blue-grey in the N to brown in the S as the silt content increases. Local colour variations include turquoise, which is due to the presence of vivianite, a hydrated iron phosphate, $Fe_3 (PO_4)_2 .8H_2O$, and is seen in VC9 from 0.05 m to 0.55 m and 1.22 m to 1.66 m (Figs 1 and 10B). The clay contains abundant benthonic foraminifers, including specimens reworked from the Crag and the Chalk, also ostracods, large centric diatoms, and much plant debris. Fragments of bryozoans, echinoid spines and larval bivalves occur in most samples. The fossil content shows that this alluvium is likely to be Holocene in age (Funnell, personal communication).

The clay covers most of the study area, lying directly on the Norwich Crag Series, and appears to be thickest 4-5 km E of the Minsmere Cliffs area, where at least 3.4 m were detected without the base being reached. It thins out to the SE of Southwold, in the area of buried channels, and also to the NE of Thorpe Ness. The offshore deposits of alluvium are almost certainly continuous with those found onshore in the Minsmere Nature Reserve, and Dingle and Corporation Marshes N of Dunwich. The continuations of these two alluvial areas appear to merge offshore E of Minsmere and Dunwich Cliffs. Figure 12 is a sketch-map showing the probable extent of the alluvial clay. The surface appears to be relatively flat, forming a platform on which the Sizewell-Dunwich Bank rests.

6.4 Gravel

The gravels are represented in the geophysical interpretation as Unit 4 and comprise mainly rounded, subangular or angular flints. They are orange-brown in

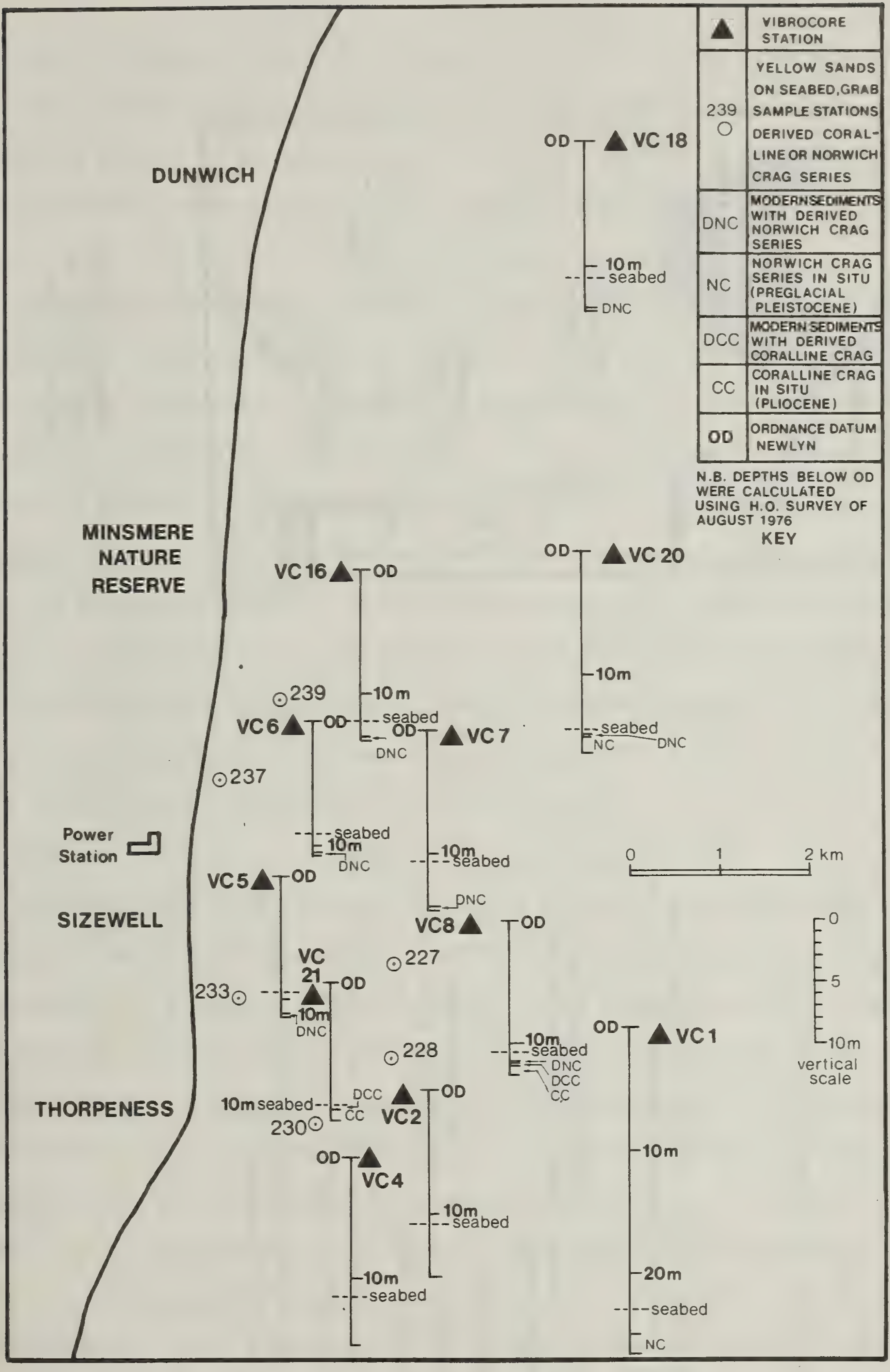
DUNWICH
MINSMERE NATURE RESERVE
Power Station
SIZEWELL
THORPENESS
VC 18
VC 20
VC 16
VC 6
VC 7
VC 5
VC 21
VC 8
VC 1
VC 2
VC 4
OD
10m
20m
seabed
DNC
NC
DCC
CC
239
237
233
227
228
230
▲ VIBROCORE STATION
239 ○ YELLOW SANDS ON SEABED, GRAB SAMPLE STATIONS DERIVED CORALLINE OR NORWICH CRAG SERIES
DNC MODERN SEDIMENTS WITH DERIVED NORWICH CRAG SERIES
NC NORWICH CRAG SERIES IN SITU (PREGLACIAL PLEISTOCENE)
DCC MODERN SEDIMENTS WITH DERIVED CORALLINE CRAG
CC CORALLINE CRAG IN SITU (PLIOCENE)
OD ORDNANCE DATUM NEWLYN
N.B. DEPTHS BELOW OD WERE CALCULATED USING H.O. SURVEY OF AUGUST 1976
KEY
0
1
2 km
0
5
10m
vertical scale

Fig. 11

Location of iron-stained sands on seabed surface and in vibrocores

Key for Figs 4 (p.7) and 13 (p.25)

a Exposures of rock ridges (Coralline Crag), with strike direction as shown by sidescan sonar.

b Gravel. Angular and rounded pebbles, mainly orangey flints. Good fauna, mainly sessile forms.

c Medium sand }
d Fine sand } Clean, brownish to yellowish, firm.
e Very fine sand }

f Intercalated sands, silts and clays Mainly grey. 'Fluid'.

g Sticky blue-grey clay, often with veneer of brown silt or sand

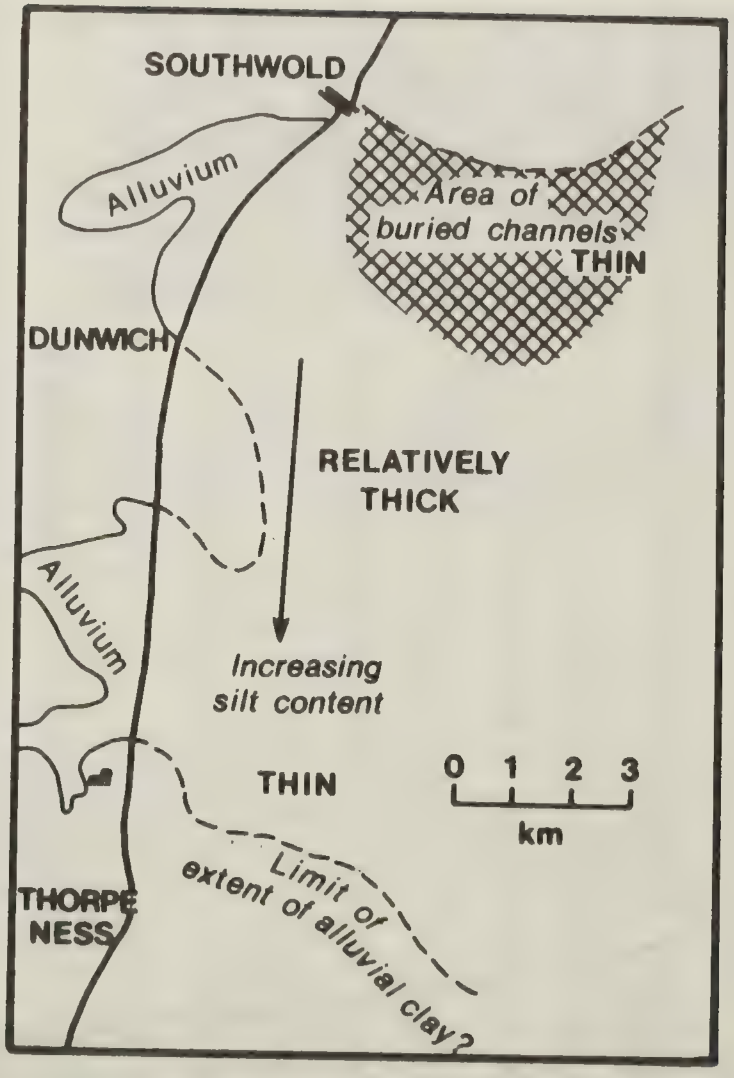
SOUTHWOLD
Alluvium
Area of buried channels
THIN
DUNWICH
RELATIVELY THICK
Alluvium
Increasing silt content
THIN
0 1 2 3
km
THORPE NESS
Limit of extent of alluvial clay?

Fig 12 Schematic diagram of distribution of alluvial clay

colour and the maximum length of the pebbles sampled is 80 mm. Quartzite, quartz and a small number of other types are also present. The indigenous fauna on the surface gravels is mainly sessile, indicating stability of the sediment at the present time. This interpretation is further supported by algal and other staining on the lower halves of the pebbles only.

The surface distribution of gravel is depicted on the 1975 sediment distribution map (Fig 4). Often the gravel forms a veneer and the grab penetrated to the sands or clays beneath, resulting in the inclusion of very fine to medium sands, with whole, fragmented and comminuted shell, or silts and clays. A depth measurement of the gravel 2 km seawards of the sand/gravel boundary showed a thickness of only 0.09 m.

As well as the surface exposures, gravel has also been located forming the infill of the buried channels. These sediments comprise rounded and subangular pebbles in very fine to coarse sand matrices with occasional bands of silt and clay.

Beneath the main gravel exposure, near the eastern boundary of the study area, a 0.18 m thickness of chalk has been found at a depth of 0.22 m. This is interpreted as an erratic and is thought not to be chalk in situ.

6.5 Intercalated sands, silts and clays

The sands, silts and clays are correlated with Unit 3 of the seismic profiling interpretation. They are usually grey or brown in colour, becoming darker with depth and are of a rather fluid consistency. X-ray photographs of box cores show that the sands are intercalated into the silts and clays with layers of varying thickness. Owenia fusiformis, a tube worm, was present in large numbers in the order of 1.5×10^3 individuals m^{-2}, far outnumbering animals of any other species visible to the naked eye in any of the samples taken. Bamber and Coughlan (1980) consider that these tube worms would have imparted stability to the sediment. The micropalaeontological content of the clays presents a similar general aspect to the blue-grey clays described above (Funnell, personal communication).

Variation of the surface distribution of the sands, silts and clays has been demonstrated during the course of the study. Fig 4 shows the distribution in

February 1975, and Fig 13 that in August 1978. A bedload transport measurement experiment, using precise positioning equipment and fluorescent tracer (Lees,1980b) gave additional data on the sequence of changes, but in a limited area, at the SE corner of the Dunwich Bank. The sequence was as follows: April 1975, sand; March 1978, sand (one vibrocore); August 1978, sands, silts and clays; October 1978, sands, silts and clays; February 1979, sand; April 1979, sands, silts and clays. This varying distribution is also reflected in certain of the cores when bands of sand alternate with the sands, silts and clays. At present it is not possible to suggest a time scale for this banding.

The sands, silts and clays appear to be partly derived from the bank sand, and partly from the top of the alluvium, with additional material from other sources, perhaps outside the area.

6.6 Bank sand

The most important sand area is that which includes the banks (seismic Unit 2). The sand is compact, clean and varies in colour from creamy-grey to brown. Very little iron-staining is shown. There is a high percentage of quartz, many grains being angular with a few exhibiting frosted surfaces. Surface textures alone, however, are not sufficient basis for the determination of environmental origins (Soutendam, 1966; Baker, 1966). A little glauconite is present. Many samples contain comminuted shell, or laminae of entire and fragmented shell, all of unaltered appearance. Bioturbation is also shown in some samples, with worm burrows and sea-urchin feeding trails. Clay pellets found in some of the sand samples from the eastern part of the banks are likely to be erosion products from the intermittent exposure of the underlying sediments.

Surface samples from the banks comprised mainly very fine sand in 1975, with some fine and a little medium sand towards the edges (Fig 4). In 1978 there appeared to be a higher proportion of fine sand (Fig 13). A range of mean grain sizes from 3.38φ to 2.19φ ie very fine to fine sand (Table 2) was given by the 1977 box core samples. The 1975 grab sample mean values (Table 2) have been

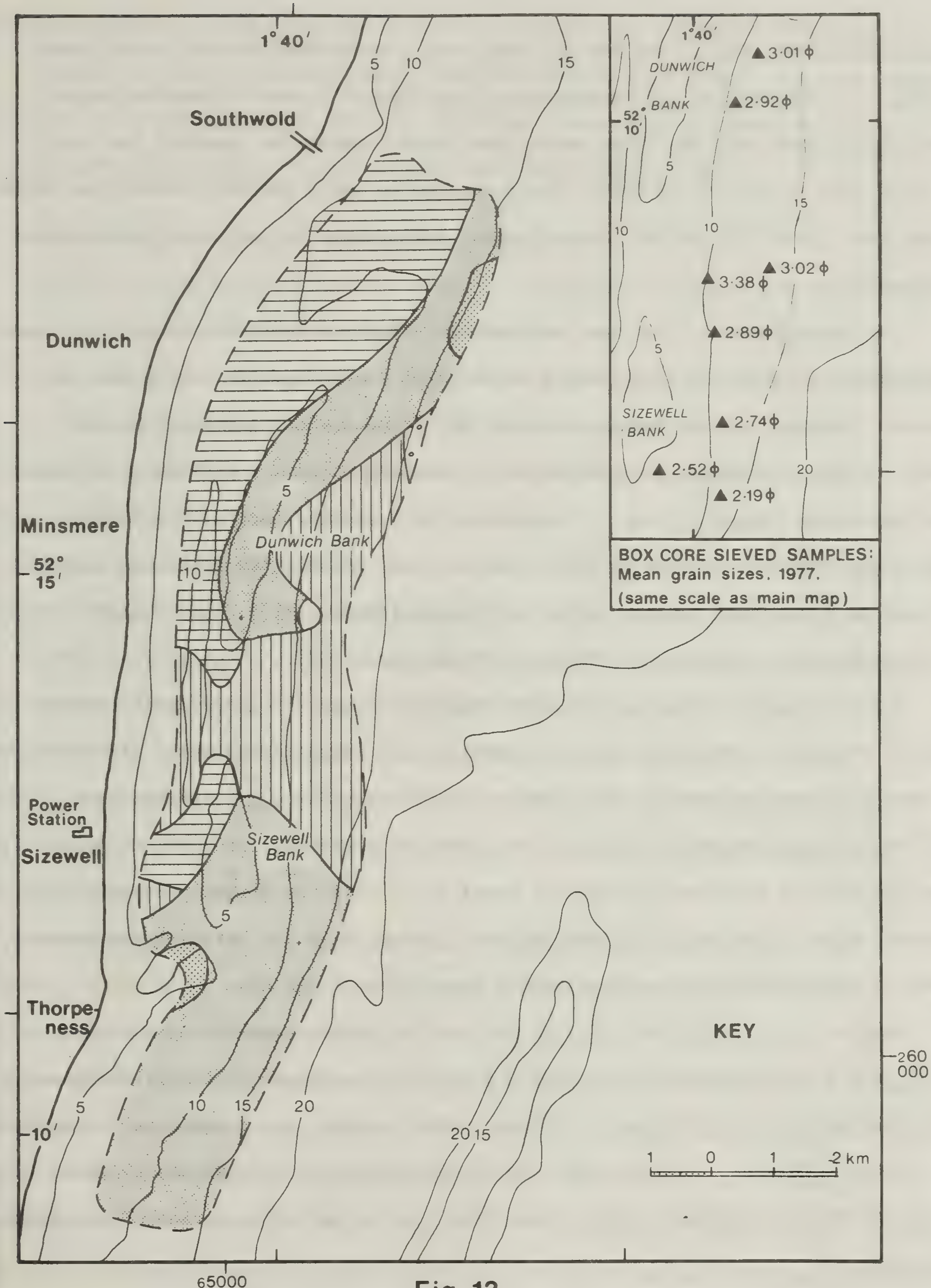
1° 40′
5
10
15
Southwold
Dunwich
Minsmere
52°
15′
10
5
Dunwich Bank
Power
Station
Sizewell
Sizewell
Bank
5
Thorpe-
ness
5
10
15
20
-10′
20 15
65000
KEY
260
000
1
0
1
2 km
1°40′
DUNWICH
BANK
52°
10′
5
10
10
15
▲3·01 ϕ
▲2·92 ϕ
▲3·02 ϕ
▲3·38 ϕ
▲2·89 ϕ
5
SIZEWELL
BANK
▲2·74 ϕ
▲2·52 ϕ
▲2·19 ϕ
20
BOX CORE SIEVED SAMPLES:
Mean grain sizes. 1977.
(same scale as main map)

Fig. 13

Fig 13 Sediment distribution, August 1978, with inset showing mean grain sizes for box core sieved samples, 1977. SEE FIG. 4 and P.22

incorporated into Fig 4, and the box core sample means are included as an inset to Fig 13. The statistical parameters of the limited number of samples which were sieved show that the finer sands were found towards the crest of the bank in 1975, and in the col in 1977. The consistently small standard deviations which range from 0.26ø to 0.64ø are indicative of well-sorted to moderately well-sorted sediments.

The distribution of the sand surface has also been found to change with time. A comparison of the 1975 grab sample survey with the background survey for the bedload transport measurements of August 1978 (Figs 4 and 13) shows that the Dunwich Bank sand became less extensive to both the W and E and thereby uncovered the underlying blue-grey clay. In contrast the veneer of sand at the northern end of the bank was thicker in 1978. The col area between the banks was composed of sand at the seabed surface in April 1975 and February 1979, but of soft clays, silts and sands in August and October 1978 and April 1979.

The thickness of the sand has been determined from the geophysical records (Fig 6) with the vibrocores adding further detail where appropriate. Its base is easily recognised beneath the crest of the Dunwich Bank, but becomes more difficult to distinguish further S. The sand has a maximum thickness of 9.5 m over the Dunwich Bank and probably at least 7.3 m over the Sizewell Bank. The sediment shows a seismically structureless layer up to 2.0 m thick at the surface, possibly representing the surface mobile layer (Fig 7A and B).

Sand in VC12 (Fig 1 and 10B), in the area of buried channels, was 0.59 m thick, but it lay beneath 0.54 m clay. The sand is sedimentologically different from the Bank Sand, particularly in being poorly sorted, and containing virtually no calcium carbonate, compared with 15% in the Bank Sand. It therefore cannot be classified as Bank Sand, but is more likely to be part of a series of estuarine deposits.

Vibrocores located SE of Thorpe Ness penetrated sand with a thickness of 1.42 m of coarse and medium sand and 1.12 m of fine and very fine sand showing current bedding. Again these sands are not part of the bank sands sensu stricto.

There is a zone of medium sand to the E of the area of sands, silts and clays seaward of the Sizewell Bank (Fig 4). However, these sand sediments are some distance from the study area and have not been analysed further.

7. Sedimentation Sequence and Quaternary History

From the evidence already available it is possible to deduce the sedimentation sequence and outline the Quaternary history of the area. It is the author's intention to develop the evidence during future work by a more detailed analysis of the foraminiferal and possibly also the pollen content of the sediments.

Schematic sections, one parallel to the shore, and two normal to it are shown in Fig 14, to clarify the interrelationships of the Quaternary sediments.

The only pre-Quaternary rock identified in the area is the Pliocene Coralline Crag, a ridge of shelly, iron-stained sand outcropping in the SW of the area as an ENE-WSW continuation of the core of Thorpe Ness. Lying unconformably against this ridge are the shelly clays, sands and gravels of the Norwich Crag Series, underlying the Holocene sediments covering the remainder of the study area. The erosion surface of these beds dips to the E, but there is no evidence for the direction of dip within the Crag strata. Both the Crags have been identified by their macrofossil content.

The recognition of the alluvium from its microfossil content as being probably of Holocene age, together with the infilling and burial of channels SE of Southwold, is evidence of a post-Pleistocene marine transgression. The erosion of the Norwich Crag Series referrred to above could have occurred at least partially during this transgression. However Carr and Baker (1968) and Carr (1971) who worked in the Orford and Shingle Street area immediately S of Aldeburgh, considered that the evidence there indicated the Pleistocene planation of a similar surface. The buried channels could have been initiated during the late Pleistocene. Alluvial clay has been recognised onshore and it is reasonable to suppose that it is part of the same deposit as that offshore and that the transgression reached

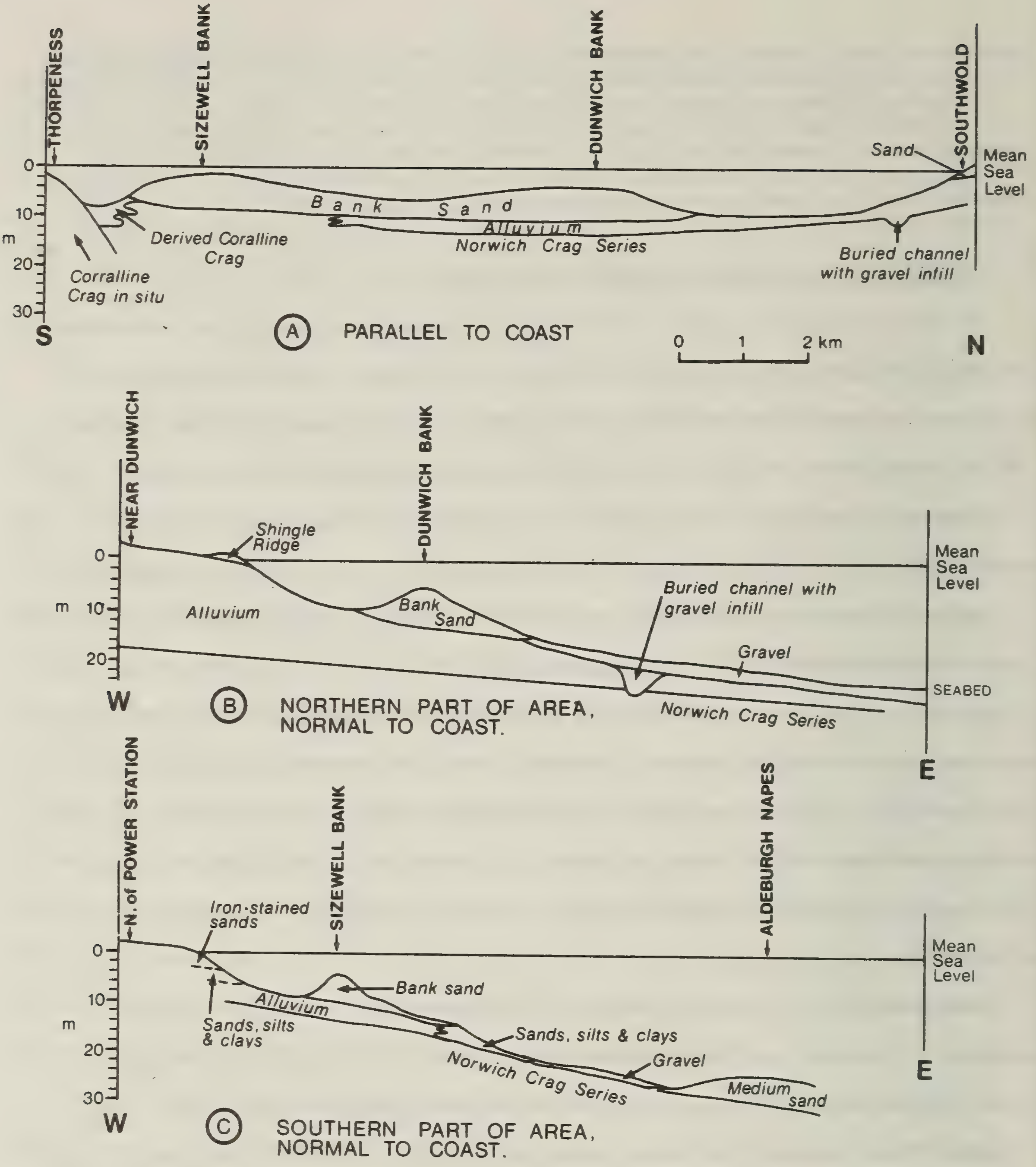
THORPENESS
SIZEWELL BANK
DUNWICH BANK
SOUTHWOLD
Sand
Mean Sea Level
0
10
m
20
30
Bank Sand
Alluvium
Norwich Crag Series
Derived Coralline Crag
Corralline Crag in situ
Buried channel with gravel infill
S
N
A
PARALLEL TO COAST
0 1 2 km
NEAR DUNWICH
DUNWICH BANK
Shingle Ridge
Mean Sea Level
Alluvium
Bank Sand
Buried channel with gravel infill
Gravel
SEABED
Norwich Crag Series
W
E
B
NORTHERN PART OF AREA, NORMAL TO COAST.
N. of POWER STATION
SIZEWELL BANK
ALDEBURGH NAPES
Iron-stained sands
Mean Sea Level
Bank sand
Alluvium
Sands, silts & clays
Sands, silts & clays
Gravel
Norwich Crag Series
Medium sand
W
E
C
SOUTHERN PART OF AREA, NORMAL TO COAST.

Fig.14

Fig 14 Schematic sections of seabed. A. Parallel to coast.
B. Northern part of area, normal to coast.
C. Southern part of area, noraml to coast.

inland to where the present deposits of alluvium are found. As far as the author is aware, there has been no investigation of these clays for dating, either from peat horizons, or microfossil content, but they may be similar to estuarine clays both to the N and S of the area. Carr and Baker (1968) gave radiocarbon dates of 8460± 145 y BP and 3460± 100 y BP for peat samples occurring within estuarine clays in the Orford area, similar evidence to that given by Coles and Funnell (1980) for two marine incursions, c 7,5000 y BP and c 2,000 y BP in the Broadland valley of East Norfolk.

At the time of the transgression, the Minsmere and Dunwich Cliffs extended further E than now, providing an area between two river valleys more resistant to the incursion of the sea.

Following a relative lowering of sea-level, the sea withdrew to at least a shoreline near the present coastline in the S, and perhaps further E in the N, allowing the river Blyth to form several estuarine channels. Perhaps these were superimposed on the earlier drainage pattern postulated above. This may account for geophysical evidence which apparently shows two channels lying close together (Fig 8A and B). Vivianite, mentioned above, is often associated with clays deposited in estuarine channels because a source of phosphate is provided by fossil bones and shells (Read, 1972). Also flowing into what was the same broad estuary would be rivers from the Walberswick and the present Minsmere Nature Reserve areas. There were probably sand and gravel ridges further offshore, perhaps forming a barrier beach.

A relative sea-level rise then resulted in an advance of the sea, probably carrying material from the ridges shorewards. This infilled the estuarine channels and may have provided a source of material for the formation of sand and shingle ridges acrosss the valleys, ie the beach ridge at Walberswick, the sand and shingle barrier ridge immediately N of Dunwich, and the ridges and subsequent sand dunes dividing the Minsmere Nature Reserve and the Sizewell Power Station property from the sea.

During the time of transgression coastal erosion continued and is continuing intermittently, and Carr (1979) has described in detail the changes since 1836.

The interaction between tidal dynamics and the material supplied to the offshore area, both from this stretch of the coast, and possibly to the N and S, resulted in the formation of the Sizewell-Dunwich Banks, aligned parallel to the shore, and approximately 2 km from it. The banks themselves comprise clean, well-sorted sand, but at the eastern edge and in the col there appear to be seasonal changes between the clean sand and intercalated sands, silts and clays. The latter may be partially derived from erosional products of both the periphery of the sandbank and the alluvial clays.

The future structural trend of the Sizewell-Dunwich Bank may be to form two completely separate banks. The bank is also migrating towards the shore (Carr, 197

8. Acknowledgements

Financial support for the Sizewell-Dunwich Banks Field Study, of which this work is a part, is provided by the Department of the Environment.

I would like to thank Professor B M Funnell of the University of East Anglia for a qualitative analysis of the microfossils in the clays, and Mr R Markham, of Ipswich Museum, for identifying the macrofossils in the iron-stained sediments. I am also grateful to Dr R Kirby for his expertise when obtaining the vibrocores, and Mrs C Kemp for her care in drawing the figures. I am indebted to all my colleagues at the Institute of Oceanographic Sciences (Taunton) for help at all times and particularly to Dr A P Carr and Dr K R Dyer for constructive criticism of the manuscript. The author, however, is still entirely responsible for any remaining errors.

TABLE 1

Classification of the sediment types in the Sizewell-Dunwich Banks area

PERIOD	EPOCH	SERIES/FORMATION	UNIT	
Quaternary	Holocene		Bank sand (Seismic Unit 2) }	Intercalated sands, silts and clays (Seismic Unit 3)
			Gravel (Seismic Unit 4)	
			Blue-grey clay (Seismic Unit 1)	
	Pleistocne	Norwich Crag Series		
Tertiary	Pliocene	Coralline Crag		

BLE 2

ain size analysis of selected grab and box core samples

pe of sample and number	% of mud	% of sand	% of gravel	Mean of sand fraction	Standard Deviation of sand fraction
ab sample (1975)					
128	Nil	94.2	5.8	1.060	0.710
141	8.7	91.3	Nil	3.09	0.46
143	Nil	100.0	Nil	2.55	0.26
169	Nil	100.0	Nil	2.12	0.58
core (1977)					
12	5.8	94.2	Nil	3.38	0.64
14	1.0	99.0	Nil	2.89	0.32
18	0.3	99.7	Nil	2.52	0.47
20	0.3	99.7	Nil	2.19	0.48
23	1.0	99.0	Nil	2.74	0.33
31	2.0	98.0	Nil	3.02	0.43
37	1.0	99.0	Nil	2.92	0.43
41	1.6	98.4	Nil	3.010	0.380

TABLE 3 List of macrospecies found in iron-stained sands from vibrocores

Vibrocore number + depths	Lamellibranchiata	Gastropoda	Other species	Age
1 2.18 m to 3.64 m	Yoldia lanceolata Mytilus edulis Spisula Chlamys opercularis group Macoma praetenuis? Cardium edule group Mya	Littorina	Barnacle valves	Norwich Crag Series
5 1.52 m to 1.77 m	Nucula "Mactra" Macoma balthica Abra Cardium + derived Norwich Crag Series forms: Mytilus, Chlamys, Cardium, Yolidia, Littorina			Recent
6 1.64 m to 1.70 m	Nucula Macoma balthica			Recent
7 3.95 m to 3.98 m	Nucula Macoma	Hydrobia		Recent
8 1.24 m to 1.56 m	Nucula "Spisula" Macoma balthica Ostrea	Hydrobia Buccinum		Recent
1.56 m to 2.09 m	Ostrea Chlamys + Coralline Crag "Rockbed"		Bryozoa Regular echinoid (fragment) Barnacle valves	Coralline Crag
16 1.17 m to 1.47 m	Nucula "Spisula" Abra	Hydrobia		Recent

TABLE 3 (contd).

Vibrocore number + depths	Lamellibranchiata	Gastropoda	Other species	Age
18 2.58 m to 2.69 m	Nucula			Recent
20 0m to 0.17 m	Nucula Mytilus edulis			Recent
0.17 m to 1.87 m	Yoldia lanceolata Mytilus edulis Spisula Chlamys opercularis group Cardium Macoma ?praetenuis Macoma ?obliqua Ensis Corbula Hiatella arctica	Nucella Buccinum Turritella ? incrassata	Barnacle valves	Norwich Crag Series
21 0.13 m to 1.19 m	Chlamys opercularis group Coralline Crag "Rockbed"	Scala	Bryozoa Barnacle valves	Coralline Crag

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A NOTE ON SUPPOSED CRAG SHELLS FROM THE KIPPETT HILLS, ABERDEENSHIRE

P.G. Cambridge*

At the beginning of the century, when research on the Plio-Pleistocene was at its height, and the Crag deposits of East Anglia were being extensively studied, a number of records of isolated material from other parts of the country were made. Some of these, like the St. Erth Clays, Cornwall have been re-studied; of others there appears to have been no further record in the literature. Among the latter was a record of "Crag" fossils from gravels in Aberdeenshire by T.F. Jamieson (QJGS 1882 Vol 38, "On the Crag Shells of Aberdeenshire"). Jamieson's specimens do not seem to have been preserved so that comments on his determinations are purely speculative but it is interesting to note that he believed that "some bed as old at least as the Red Crag of Norfolk (sic) must have contributed to the remains".

If the molluscan species were correctly identified, then a Red Crag origin is most likely. Some of the species in his list might have come from earlier deposits but they all occur either as contemporaneous or derived shells in the Red Crag with the exception of _Macoma balthica_ (L). Thus _Scaphella lamberti_ (Sowerby) lived in Pliocene times and is found in the Lower Red Crag (Sands of Walton). It also occurs in the Upper Red Crag as worn fragments, especially pieces of the columella and apex. Jamieson describes his specimen of _Scaphella_ as a much worn fragment of the columella. It is doubtful whether such a fragment could be used to decide whether the species is _S. lamberti_ of the Pliocene or _S. bolli_ (Koch) of the Miocene. Similarly, worn or fragmentary shells of _Glycymeris_ are very difficult to determine in the absence of a definite age for the specimens since the genus is well represented from the Eocene to the present day.

Having examined recently collected specimens from the Kippett Hills I consider that there is some doubt about the real age of these specimens. All were

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extremely fragmentary, worn and partially decalcified. The matrix of the specimens, described by Jamieson as a "hard calcareous paste or concrete" is unlike any of the East Anglian Crags and no sand or glauconite grains were noted. However, there is no reason to expect that a similar age would mean a similar lithology, especially over such large distances.

None of the first batch of specimens examined by myself could be identified with absolute certainty. A very worn gastropod was definitely sinistral and, if from the Red Crag, would almost certainly have been determined as Neptunea contraria c. var informis Wood. This is a small, depressed form also found in glacial gravels in Ireland. Such determinations are based solely on an assumed age and since the age can only be determined by naming adequately preserved material, the arguments become circular. Due to subsequent breakage of the "Neptunea" a complete bivalve was discovered within the matrix of the interior. Although rather decalcified it could be identified as Corbula gibba Olivi. It is unfortunate that this is a long ranging species, found from the Upper Miocene to the present day, and therefore does not add to the evidence for the age of the bed.

Shelly material in glacial gravels is sometimes a mixture of more than one age (i.e. Waterford, Ireland; Keyingham, Yorkshire). Similar mixed accumulations occur in submarine gravels in the Southern Bight of the North Sea at the present day and such a mixed assemblage cannot be discounted for the time being for the Kippett Hills Gravels. While it does not seem possible with the present material to be more definite, it does show that material can still be collected and that the opportunity for finding determinable material still exists.

I am most grateful to Mr. Rodger Cornell for the opportunity to examine his specimens and for his permission to comment on them.

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AMINO ACID RATIOS IN CRAG MOLLUSCS

[illegible]

A.M.C. Davies*, A.M. Funnell** and B.M. Funnell***

Summary

Analysis of the alloisoleucine: isoleucine ratios resulting from post-mortal epimerisation of L-isoleucine in the shells of fossil Mya from the Red and Norwich Crag Formations gives results ranging from 1.19 in the Red Crag of Bawdsey to 0.58 in the presumed equivalents of the Norwich and Weybourne Crags at Crostwick. There is however very considerable variability and overlap in values from different stratigraphical levels (Red Crag 1.19 to 0.83; Ludham Crag 1.07 to 0.63; Norwich Crag 1.20 to 0.76; Weybourne Crag 0.94 to 0.58).

Introduction

In 1979 Miller, Hollin and Andrews published the results of amino acid analyses of some Crag molluscs and foraminifers collected and selected for analysis by P.G. Cambridge and B.M. Funnell. This paper presents the results of further amino acid analyses carried out on samples of Mya from outcrop and borehole materials from East Anglia during 1979. The specimens were again provided by P.G. Cambridge and B.M. Funnell, and prepared for analysis by A.M. Funnell. The amino acid ratios were determined by A.M.C. Davies using the facilities of the Analytical Services Group of the Food Research Institute, Norwich.

Basic considerations

The calcareous shells of molluscs are secreted in life on an organic, proteinaceous matrix. The proteins which fulfil this function become totally enveloped during this process in mineral material, which protects them after death from immediate biological or chemical destruction. Decomposition of the high molecular weight proteins, first into shorter chain-length peptides, and then into discrete amino acids does however occur spontaneously after death, within the enveloping mineral skeleton. The rate at which this decomposition proceeds depends, *inter alia*, on the ambient temperature, and the extent on the length of

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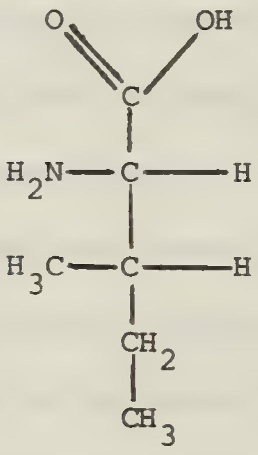
time elapsed.

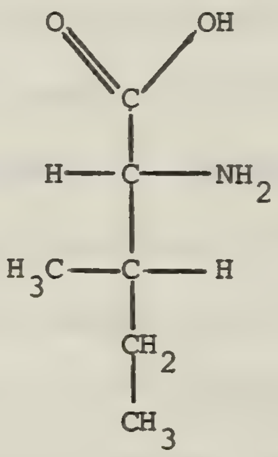
Most amino acids contributing to peptide and protein molecules contain at least one carbon atom that is asymmetric (i.e. it can occur in one or other of two different orientations). The compounds containing the two differently orientated carbon atoms are known as isomers of one another, strictly speaking stereoisomers. Pure stereoisomers have the property of rotating light that is passed through them. Therefore they are referred to as L- (= laevo = left-handed) or D- (= dextro = right-handed) forms. Biological processes based as they ultimately are on DNA base sequences in the genetic code, always produce only one of the two possible stereoisomers of any amino acid.

A few amino acids contain not one but two asymmetric carbon atoms. These produce not two, but up to four isomers, known as enantiomers. There are two normal (L- and D-) forms and two (also L- and D-) forms designated allo. Both stereoisomers and enantiomers produced biologically will revert in time to an equilibrium mixture of the two or four forms. With stereoisomers this process is known as racemisation, with enantiomers it is known as epimerisation. These processes occur spontaneously within shell material and like the breakdown of proteins to peptides and peptides to amino acids, the rate at which they proceed and the extent to which they proceed appear to be largely temperature and time dependent.

A particularly interesting epimerisation is that of L- isoleucine to D-alloisoleucine.



L-isoleucine



D-alloisoleucine

In original shell material only L- isoleucine is present. At the conclusion of epimerisation the equilibrium ratio of D- alloisoleucine to L- isoleucine is 1.30 ± 0.05 (Miller *et al*. 1979). Very small differences in the allo/iso ratio can be measured by ion-exchange chromatography. Because the reaction rate is mainly temperature and the extent of the reaction time dependent the ratios observed in fossil shells which have had similar thermal histories should indicate the relative ages of the shells in which they are determined.

Previous results

Miller *et al*. (1979) reported the results of amino acid analysis of 42 bivalve shells and 3 foraminifer samples from the Crags of East Anglia. The bivalves analysed were *Corbicula* (three samples from one site), *Mya* (twenty-three samples from nine sites), *Macoma* (sixteen samples from six sites), and the foraminifer *Elphidiella hannai* (three samples from three levels in a borehole at one site). The highest (≡ oldest) D- alloisoleucine : L- isoleucine ratio observed was 1.20 ± 0.02 from *Mya* shells in the Coralline Crag, the lowest (≡ youngest) 0.76 ± 0.021, from freshwater *Corbicula* shells in the Norwich Crag of Wangford. Clearly the value from the Coralline Crag shell is approaching the equilibrium value of 1.30 ± 0.05 at which epimerisation would be complete. The value of 0.76 ± 0.021 obtained on *Corbicula* from the Norwich Crag of Wangford is probably not the youngest sample examined. *Mya* from the same site gave a value of 0.89 ± 0.043; a value for *Mya* of 0.86 ± 0.028, was obtained by Miller *et al*. (1979) from the Weybourne Crag of West Runton which biostratigraphically appears to be the youngest Crag sample examined by then.

Present Results

The results obtained in the present investigation are given in Table 1. All determinations were made on fragments of *Mya* shells (for details of methods see Appendix 1 on Experimental Procedures). All results obtained are presented. A few (11A, 12B, 13B, 18A, 24A, 26B) are clearly spurious, but there is no obvious reason why they in particular should be so. Vial 12B failed (i.e. cracked)

Table 1. Alloisoleucine: isoleucine ratios in *Mya* shells from the Crags of East Anglia

Sample No.		allo µg		allo/iso ratio	
		(A)	(B)	(A)	(B)
1	Bawdsey (Red Crag, cliffs)	0.0788	0.1759	1.12	1.19
2	" " " "	0.1134	-	1.06	-
3	Butley (Red Crag, Neutral Farm Pit)	0.0911	0.0915	0.80	0.90
4	Chillesford (*Scrobicularia*	0.0474	-	0.90	-
5	" Crag, Church Pit)	-	0.1760	-	0.94
6	Aldringham (Norwich Crag,	0.0301	0.0728	0.96	0.99
7	" Shell Cottages Pit)	0.0901	0.1362	0.78	0.92
8	Bulchamp (Norwich Crag,	0.1113	0.1901	0.83	1.13
9	" Union Farm Pit)	0.0826	0.0132	1.09	1.20
10	"	0.1324	0.0484	1.01	0.89
11	Wangford (Norwich Crag, Hall Farm Pit)	0.0505	0.0574	1.78	0.90
[a]12	Bramerton (Norwich Crag,	0.1080	0.0373	1.21	1.70
[a]13	" Blake's Pit)	0.0851	0.0080	1.10	0.37
[b]14	"	0.2131	0.2146	1.17	0.99
[c]15	" (Norwich Crag, Common Pit)	0.0940	-	0.96	-
[d]16	Crostwick (Norwich Crag,	0.0364	0.0423	0.90	0.76
[e]17	" Dobb's Plantation)	0.0122	0.0315	0.40	0.69
[f]18	"	0.1786	0.1309	1.34	0.58
[f]19	"	0.0554	0.0829	0.94	0.84
[g]20	"	0.0449	0.0501	0.68	0.87
[g]21	"	0.2120	0.1811	0.87	0.89
22	West Runton (Weybourne Crag)	0.0766	0.0772	1.04	0.94
[h]23	Stradbroke (Ludham Crag,	0.0675	0.0620	0.94	1.07
[h]24	" NERC borehole)	0.0751	0.0580	1.89	0.63
[i]25	"	0.0892	0.0534	1.09	0.97
[i]26	"	0.0987	0.1251	1.06	0.39
[j]27	"	0.0678	0.0669	1.04	0.85
[j]28	"	0.0376	0.0603	0.87	0.79
[k]29	Ludham (Ludham Crag,	0.1253	0.1566	0.49	0.93
[l]30	" Royal Society borehole)	0.0759	0.1043	0.44	0.70

Footnotes to Table 1

(A) unhydrolysed, i.e. free amino acid

(B) hydrolysed, i.e. bound amino acid + unhydrolysed, i.e. free amino acid

a	lower shelly sands	g	Horizon 8 (see Funnell 1980)
b	top shell bed	h	209 feet below surface
c	top shell bed	i	199 feet below surface
d	Horizon 1 (see Funnell 1980)	j	188 feet below surface
e	" 4 " " ")	k	-85½ (3) spec 12 (12a 10)
f	" 7 " " ")	l	-85½ (1) spec 4 (12a 0)

during the 22 hour heating period and had lost 50% of the fluid before the end of the period, but other similar failures (9B, 10B, 21B, and 29B) do not appear to give anomalous results. Neither do 1B and 14B which completely or almost completely dried out under similar circumstances.

Initial comparisons with the results obtained by Miller *et al.* (1979) are encouraging. *Mya* samples from Butley, Chillesford, Bramerton, Bramerton Common and Wangford were deliberately analysed to enable direct comparisons with their results.

Site	Alloisoleucine/isoleucine ratio	
	Miller *et al.* (1979)*	this paper*
Wangford	0.89 ± 0.043	0.90
Bramerton Common	1.02 ± 0.035	(0.96)
Bramerton	0.96 ± 0.062	0.99
Chillesford	0.94 ±	0.94
Butley	0.97 ± 0.098	0.90

(* the figures quoted are for (B) the total, i.e. free + bound amino acid content, except for the one figure in brackets which is for the free amino acid content only).

Samples 1 and 2 come from the Red Crag of Bawdsey cliffs and give a (B) ratio of 1.19 (an (A) ratio of 1.09); sample 3 comes from the Red Crag of Neutral Farm, Butley and yields 0.90 (cf. 0.97 ± 0.098 of Miller *et al*. 1979). Current thinking (Beck *et al*. 1972, Funnell and West 1977) would suggest that the Red Crag of these two localities equates with the Pre-Ludhamian pollen stage, although it should be emphasised that no pollen has yet been found in these deposits at outcrop.

Samples 23-28 come from depths between 188' and 209' below surface (i.e. c. -2 to -9m O.D.) in the Stradbroke borehole, previously interpreted as belonging to the Ludhamian pollen stage (Beck *et al*. 1972). The free plus bound (B) amino acid ratio obtained (six samples) averages 0.86. The Ludham borehole samples 29 and 30 appear to be referable (Funnell and West 1977) to the later part of the Ludhamian pollen stage and give an average free plus bound ratio (two samples) of 0.815. So far so good, the average values for the successive pollen stages are:

Late Ludhamian	0.815,
Ludhamian	0.86,
Pre-Ludhamian	1.045

but this obscures the considerable range of individual values at each level:

Late Ludhamian	0.93 to 0.70,
Ludhamian	1.07 to 0.63,
Pre-Ludhamian	1.19 to 0.90.

It also creates difficulties regarding overlapping values with the later Thurnian to Pre-Pastonian *a* pollen stages of the Norwich Crag Formation.

Miller *et al*. (1979) obtained a (B) value of 0.89 ± 0.025 from *Mya* of the preserved late Antian (cf. Funnell and West 1962, West, Funnell and Norton 1980) of Covehithe.

Samples 4 and 5 (*Scrobicularia* Crag, of Chillesford Church Pit), 6 and 7 (Norwich Crag of Shell Cottage's Pit, Aldringham), 8 to 10 (Norwich Crag of Union Farm Pit, Bulchamp), 11 (Norwich Crag of Hill Farm Pit, Wangford), 12 - 13 (Norwich Crag of Blake's Pit, Bramerton) and 16 (Norwich Crag of Dobb's Plantation Pit, Crostwick) gives values of 0.94, 0.955, 1.07, 0.90 (cf. 0.89 ± 0.043 of Miller *et al*. 1979), 0.90 (cf. 0.96 ± 0.062 of Miller *et al*. 1979) and 0.76 respectively.

All these localities (see discussion in Funnell et al. 1979, Funnell 1980) are likely, on present evidence, to belong to the Bramertonian pollen stage; all except the Crostwick occurrence give alloisoleucine/isoleucine values that fall in the pre-Ludhamian range!

The remaining samples 14-15 (Norwich Crag, upper shell beds of Bramerton Blake's Pit and Bramerton Common), 17-21 (Norwich-Weybourne Crag of Dobb's Plantation, Crostwick) and 22 (Webourne Crag of West Runton) give values of 0.99 (cf. 0.96 ± 0.062 of Miller et al. 1979), 0.96 (free amino acid (B) value only; cf. 1.02 ± 0.035 for total amino acid of Miller et al. 1979), 0.77 and 0.94 (cf. 0.86 ± 0.028 of Miller et al. 1979) respectively. These all belong or are likely to belong to Pre-Pastonian a pollen stage (see discussion in Funnell et al. 1979, Funnell 1980 and West 1980), but the values obtained are variable and, except for Crostwick, not systematically lower than the Ludhamian values obtained from boreholes.

Discussion

This was our first attempt at amino acid determination in fossil materials, the preparation was carried out in open inorganic chemistry laboratories (although every care was taken to avoid any sample contamination), the amino acid analyses were carried out on apparatus not specially designed for the small concentrations of amino acids in fossil materials, and that replicate samples were not run. Therefore beginner's errors can be expected, and indeed we have, as recorded, some results that are clearly spurious. On the other had we have obtained results close to those obtained by Miller et al. (1979) on comparable materials, and results were obtained elsewhere are generally similar.

We may tentatively conclude that there seems to be a consistent pattern of increasing allo/iso ratios characterising the results from the Ludhamian and Pre-Ludhamian (the former based on borehole materials) ranging from 0.815 in the late Ludhamian to 1.045 in the Pre-Ludhamian. There is however a considerable range in the values obtained on individual determinations.

For the post-Ludhamian samples (all taken from outcrop) values are, however, equally high, ranging from 0.90 to 1.07, although there is no doubt on palaeontological grounds that these deposits are significantly younger than the Ludhamian and pre-Ludhamian materials previously considered.

Only the presumed Pre-Pastonian _a_ samples from Crostwick give clearly lower values, averaging 0.77. Although the Pre-Pastonian _a_ of West Runton gave Miller _et al_. (1979) a value of 0.86 ± 0.028, it yielded us 0.94, and the upper shell beds at Blake's Pit Bramerton and Bramerton Common gave us 0.99 and 0.96* (*free amino acid (A) value only) compared with 0.96 ± 0.062 and 1.02 ± 0.035 for Miller _et al_. (1979).

Part of the reason for the variability of results at any one locality and for the absence of overall systematic temporal pattern may be the existence of different amino acid compositions and variable rates of epimerisation in different parts of _Mya_ shell material, a possibility implicitly acknowledged by Miller _et al_. (1979, footnote to Table 1, relating to their samples 708 D-H) in respect of _Corbicula_, and explicitly discussed by Hare (1969) in relation to the genus _Mercenaria_. Most of our specimens for reasons of preservation or identification, (especially in borehole material) came from the hinge-line area of the _Mya_ shell. In _Corbicula_ (Miller _et al_. 1979, loc. cit.) the hinge area gave a substantially higher allo/iso ratio than the remainder of the shell, (0.24, compared with 0.17 to 0.21).

Whilst recognising that part of the variability in our results may be attributable to such intrinsic variability in gross epimerisation rates in different parts of the shell of _Mya_, it does not explain the persistent recurrence of values of 1.0 or more in shells from post-Ludhamian material collected at outcrop from relatively shallow pits or cliffs. These shells could of course be derived from older deposits. _Mya_ fragments, especially of hinge-line material, are relatively robust, persistent and readily indentifiable even after considerable attrition. However by no means all the _Mya_ material is likely to have been derived in this way. In particular the Mya from the Chillesford Crag, of Chillesford Church Pit are mostly to be found in position of growth, yet these, probably Bramertonian (i.e. post-Ludhamian) shells also gave Miller et al. (1979) a value of 1.08. The suspicion grows that values as high or higher than 1.0 in post-Ludhamian materials (and perhaps even in Ludhamian and late pre-Ludhamian) may be a function of closeness to the land surface, and may possibly be related to the thermal history of near surface sediments in the time after Pre-Pastonian a, which includes the Pastonian and Cromerian warm periods as well as later interglacials.

Conclusions

Our results do not yet encourage optimism that amino acid analysis (or at least alloisoleucine/isoleucine epimerisation ratios) of molluscs will prove readily applicable to fine-scale stratigraphical decipherment of the Crag formations. Possibly other genera than Mya may yield more consistent results, especially if analysis is systematically applied to specific parts of the shell, but consistent identification of non hingeline fragments in borehole material is not easy. Increased precision may be achieved by running sufficient replicate samples (cf. Miller et al. 1979, p.543). Also application of high sensitivity analysis to small quantities of microfossil materials may prove to be more generally applicable to borehole materials.

In the meantime we record in Table 2, in our best biostratigraphical estimate of correct stratigraphical order, the results so far obtained.

Acknowledgements

We are most grateful to G.H. Miller for personal advice and guidance on preparation procedures, to P.G. Cambridge for his continuing willingness to provide still more molluscan samples for analysis, and to Miss Adeline L.C. Wong for skilled assistance with the amino acid analysis. We also thank T.C. Atkinson and T. Wigley for carefully and critically reading our draft manuscript.

Table 2

Stage (pollen-based)	Locality	allo/iso ratios	
		this paper	Miller *et al*. (1979
Pre-Pastonian *a*	*West Runton	0.94	0.86
	Crostwick	0.77 (0.58-0.89)	-
	*Bramerton Common	0.96[1]	1.02
	*Bramerton, Blake's Pit (upper)	0.99	0.96
Bramerton	*Bramerton, Blake's Pitt (lower)	-	0.96
	Bulchamp	1.07 (0.89-1.20)	-
	*Wangford	0.90	0.89
	Aldringham	0.96	-
	*Chillesford (Chillesford Crag)	-	1.08
	*Chillesford (Scrobicularia Crag)	0.94	0.94
Antian/Baventian	*Covehithe	-	0.89
Ludhamian	*Ludham	0.82 (0.70-0.93)	-
	*Stradbroke	0.86 (0.63-1.07)	-
Pre-Ludhamian	Butley	0.90	0.97
	Bawdsey	1.19	-

(* these pollen stage assignments are supported by pollen analyses from the relevant sediments themselves. All other assignments are based on similarities of the marine microfauna to those in sediments from which pollen has been analysed.)

1 only free amino acid (A) value available

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Appendix 1:

Experimental Procedures : Preparation of samples

Preparation followed the procedures used by Miller *et al.* (1979) and Andrews *et al.* (1979) and included the following steps:

1. 100 to 400 mg of mollusc shell selected and weighed
2. 33% of shell dissolved in pre-judged amount of 2N HCl
3. Centrifuged and rinsed with double distilled water 2 to 3 times
4. Allowed to dry
5. Fragment of 40-50 mg selected and weighed to ± 0.1 mg
6. Placed in pre-weighed test tube and 0.8 ml of (2-4°C) 6N HCl (pure) added
7. Centrifuged in stoppered tube for 10 minutes
8. 0.4 ml placed in vial A, 0.4 ml in vial B
9. Vial A: dried at c. 80°C and sealed
10. Vial B: 0.4 ml 6N HCl added, flushed with N_2, sealed and placed in oven for 22 hours at 110°C. Then seal broken, contents of vial dried and resealed

A. provides a measure of the D-alloisoleucine/L-isoleucine ratio in the free amino acids (those produced by natural breakdown of peptides within the fossil).

B. provides a measure of the total D-Alloisoleucine/L-isoleucine in the free plus bound (peptide bound) amino acids.

Appendix 2:

Experimental Procedures : Amino Acid Analysis

Alloisoleucine and isoleucine were determined on a Technicon TSM amin acid analyser equipped with a microcomputer controlled buffer gradient generator (Davies *et al.* 1979). The recorder output was logged via a retransmittance slidewire on an off-line data logging system and then integrated and identified by computer (Stansfield *et al.* 1974). Because of the very small amount of amino acids present in the sample it was necessary to increase the sensitivity of the instrument fivefold and to transfer all the sample to the sample cartridge. This resulted in large amounts of calcium being put through the system and in order to prevent recipitation EDTA was added to all buffers (1g/l). The instrument was calibrated against standard amino acids, however, as it is difficult to obtain pure alloisoleucine (Laird *et al.* (1970), the amount of isoleucine in the alloisoleucine was determined and a correction made to the calibration.

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COMPOSITION OF PRE-ANGLIAN GRAVELS IN NORFOLK

R.W. Hey*

Introduction

In an earlier paper (Hey, 1976), the writer recorded pebble-counts carried out on pre-Anglian Pleistocene gravels at seven localities in Norfolk and five in Suffolk. The present paper records six additional pebble-counts from Norfolk; five of them are from new localities, the sixth is from a horizon at Sidestrand lower than any of those for which pebble-counts were presented in the earlier paper. The new results and some of the old are discussed in the light of recent developments in the study of the East Anglian Pleistocene, in particular the recognition of two new stages between the Baventian and the Pastonian: the Bramertonian temperate stage (Funnell, Norton and West, 1979) and the succeeding Pre-Pastonian cold stage (West, 1980).

Sampling localities

The positions of the sampling localities are shown in Fig. 1. Further information on them is given below, the numbers allotted being those used in the Figure.

1. TF 999256. Guist. Pit, showing unfossiliferous sand and shingle overlying Chalk. Reid (1890, 142-3) classified the deposit as an outlier of Crag, but was uncertain whether to assign it to the Weybourne or some older division.

2. TG 129182. Alderford Common. Pit, showing unfossiliferous gravel overlying Chalk. Blake (1888, 15) noted that the gravel resembled beach shingle but hesitated to classify it as Crag, preferring the non-committal term Pebbly Series.

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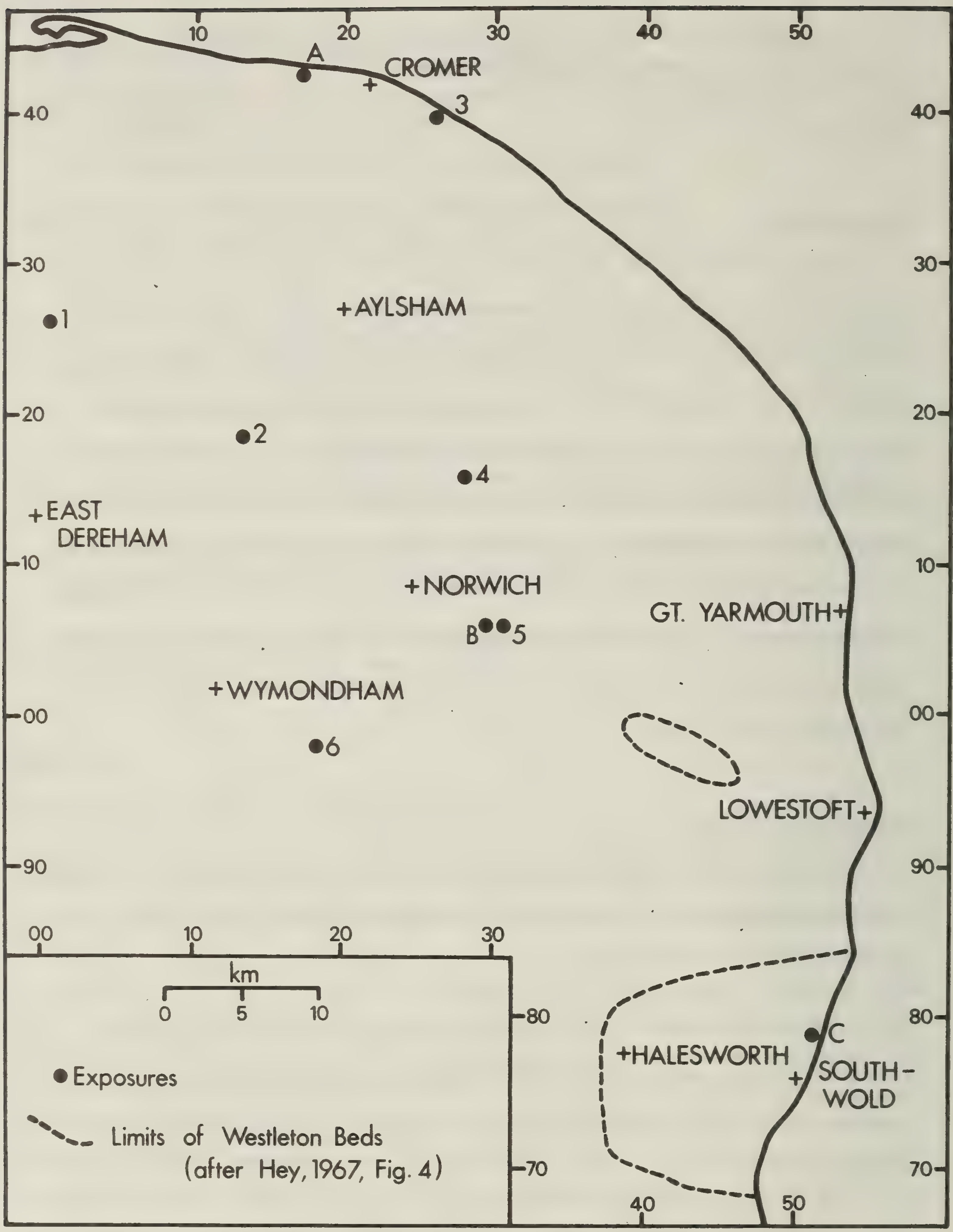
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EAST DEREHAM
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GT. YARMOUTH
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5
WYMONDHAM
00
6
LOWESTOFT
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10
20
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km
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5
10
80
Exposures
Limits of Westleton Beds (after Hey, 1967, Fig. 4)
C
HALESWORTH
SOUTHWOLD
70
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50

Figure 1 Exposures mentioned in text. Numbers are those used in text and Table 1. 1, Guist; 2, Alderford Common; 3, Sidestrand; 4, Wroxham Hall; 5, Bramerton, Blake's pit; 6, Flordon; A, Beeston Regis; B, Bramerton Common; C, Easton Bavents.

3. TG 260402. Sidestrand. Coastal cliff, section SSV of West (1980, Fig. 23), showing up to 10 m of pre-glacial Pleistocene deposits overlying Chalk. The sample was taken from the shelly basal conglomerate, assigned by West (1980, 52), on palynological grounds, to the cold Pre-Pastonian a Substage. It contains the bivalve mollusc *Macoma balthica* L. which, according to Funnell (1980, 9), probably entered the southern North Sea after the beginning of this Substage.

4. TG 272160. Wroxham Hall pit, in shelly gravel. The gravel was included by Searles Wood jun. (in S.V. Wood sen., 1866, Fig. 3 and p. 547) in his Bure Valley Beds. The mollusca, which do not include *M. balthica*, are thought to indicate a position within the earlier part of the Pre-Pastonian a Substage (Funnell, 1980, 8).

5. TG 298060. Blake's pit, Bramerton. The sample was taken from the upper shell bed, again without *M. balthica* and again assigned by Funnell (1980, 8) to the earlier part of Pre-Pastonian a.

6. TM 177975. Flordon. Pit, showing up to 10 m of unfossiliferous gravel. Woodward (1881, 70) included the whole of it in his Norwich Crag Series but recognised two subdivisions, the lower consisting almost entirely of flint pebbles, the upper containing abundant pebbles of quartz. The sample considered here was taken from the lower subdivision; the upper has been assigned by Hey (1980) to the Westland Green Member of the Kesgrave Formation, believed to comprise the earliest surviving deposits of the Thames and tentatively placed in the Pre-Pastonian a Substage.

Pebble-counts

Pebble-counts were carried out according to procedures previously described by Hey (1976, 72-3). The results are shown in Table 1.

TABLE 1. Pebble-counts (%) on sieved fractions of gravel from Norfolk sites. 1: Guist; 2: Alderford Common; 3: Sidestrand; 4: Wroxham Hall; 5: Blake's pit, Bramerton; 6: Flordon.

		1	2	3	4	5	6
16-32 mm	Flint	95.7	96.8	90.4	97.7	97.4	98.9
	Quartz	0.7	1.3	1.3	0.5	-	-
	Quartzite	1.7	1.3	0.4	0.9	0.8	1.1
	Chert, Rhaxella	0.7	-	-	0.9	1.7	-
	Chert, other	1.3	-	-	-	-	-
	Chalk	-	0.6	1.3	-	-	-
	Clay-ironstone	-	-	6.5	-	-	-
	TOTAL NO.	301	316	230	216	118	356
10-16 mm	Flint	90.6	91.7	84.4	92.8	94.8	93.1
	Quartz	3.5	4.3	4.4	3.2	0.9	4.0
	Quartzite	3.3	3.7	3.3	2.5	1.2	0.8
	Chert, Rhaxella	1.0	0.4	0.9	1.2	3.0	1.2
	Chert, other	1.6	-	-	0.3	-	0.8
	Chalk	-	-	0.5	-	-	-
	Clay-ironstone	-	-	6.5	-	-	-
	TOTAL NO.	488	564	643	848	664	247

Discussion

In the earlier paper, an attempt was made to interpret the pebble-counts then available in terms of the introduction of material into East Anglia by rivers, longshore drift and floating ice (Hey, 1976, 77-9). An attempt will be made here to interpret or re-interpret the data available for gravels now assigned to the Baventian, Bramertonian and Pre-Pastonian Stages. The three stages will be considered in chronological order.

a) Baventian

Of the four pebble-counts listed under Baventian in the earlier paper (Hey, 1976, Table II), two refer to deposits now assigned to the Pre-Pastonian a Substage. These are a conglomerate at Beeston Regis (TG 169434, Fig. 1, site A; re-dated by West, 1980, Table 1) and a pebbly sand at Bramerton Common (TG 294059, re-dated by Funnell, 1980, 9). A third pebble-count refers to Bed c of West's section SSV at Sidestrand, now thought to belong either to the latter part of the same substage or to the early Pastonian (West, 1980, Fig. 23 and Table 17).

Thus, only the pebble-count from Easton Bavents itself, on the Suffolk coast (Fig. 1, site C, TM 518787), can still be accepted as referring to a Baventian deposit. This is a shallow-marine pebbly sand; about 90% of its pebbles are of flint, the remainder of quartz, quartzite and Rhaxella chert. It is believed that the chert was derived from the Yorkshire Jurassic and carried southwards by icebergs (Hey, 1976, 78), and that most of the quartz and quartzite pebbles were ultimately derived from the Bunter Pebble Beds of the Midlands. Since they are not accompanied by any distinctive Thames material, it seems likely that the latter were carried into the North Sea by an ancestral river Trent.

b) Bramertonian

No gravel or conglomerate can yet be assigned with complete certainty to the Bramertonian Stage. Funnell, Norton and West (1979, 497) suggest, however, that the pebbly Westleton Beds *sensu stricto* are more likely to be Bramertonian than Pastonian, the stage to which they were assigned by West and Norton (1974). In composition, the Westleton gravels differ from the Baventian pebble-beds only in their higher content of flint.

The Westleton Beds rise to a known maximum altitude of 25 m O.D. (Hey, 1967, 435) and evidently represent an extensive marine transgression. The gravels sampled at Guist, Alderford Common and Flordon (lower unit) have much the same composition and rise to levels of 38, 25 and 36 m respectively. Though unfossiliferous, all are so well rounded and sorted that a littoral or shallow-marine origin seems almost certain. It is therefore suggested that they were laid down during the same transgression as the Westleton Beds themselves, and may be regarded as belonging to one and the same lithological unit.

The inclusion of all these deposits within the Bramertonian would imply downwarping towards the east in the Norwich area, for the upper boundary of the Bramertonian at its type-site (Blake's pit) lies no higher than 7 m O.D. (Funnell, Norton and West, 1979, 493-4). It may be pointed out that the upper surface of the Westleton Beds themselves descends eastwards from its maximum altitude of 25 m, near Halesworth, to only 12 m on the coast north of Southwold (Hey, 1967, 435).

c) Pre-Pastonian

Marine gravels or conglomerates assigned to the Pre-Pastonian *a* Substage have been sampled for pebble-counting at five sites: Beeston Regis and Bramerton Common (Hey, 1976, Table II, under Baventian), also Sidestrand, Wroxham Hall and Blake's pit, Bramerton (this paper, Table 1).

At Bramerton Common, Wroxham Hall and Blake's pit the composition is still of the Baventian - Westleton type, with over 90½ of flints and a few per cent each of quartz, quartzite and Rhaxella chert. At Sidestrand, pebbles of chalk and of clay - ironstone (impure siderite, probably formed within the sediment after deposition) are also present, but without these 'non-durable' constituents the composition would again be of the Baventian-Westleton type. The conglomerate at Beeston Regis, however, contains less than 75% of flints, over 10% each of quartz and quartzite pebbles, and a new arrival in the form of 'pinhole' chert, a distinctive rock which occurs _in situ_ in the Lower Greensand of the Weald. So far as is known this is the earliest marine Pleistocene deposit in East Anglia with abundant far-travelled pebbles.

The upper gravel at Flordon, already mentioned, is of a very similar composition to the Beeston conglomerate, the only difference being that it lacks Rhaxella chert. Unfossiliferous gravels of the same type, largely or wholly fluviatile, are exposed at several other localities in the Norwich area, and the writer (Hey, 1980) believes that all can be included in the Westland Green Gravels; all, in other words, are early Thames gravels. Since they extend northwards to within less than 30 km of Beeston, he has further suggested that they may be contemporary with the Beeston conglomerate, the latter being largely composed of Westland Green pebbles which had reached the coast and then been transported by longshore drift.

The Beeston conglomerate contains _Macoma Balthica_, which, as already noted, is thought to have entered the area during the Pre-Pastonian _a_ Substage. At Bramerton Common, a horizon 10.6 m above the Chalk contains abundant _Elphidiella hannai_, a foraminifer whose rise to 90% dominance in post-Baventian Crag is thought to have coincided with the arrival of _M. balthica_ (Funnell, 1980, 9). The pebble-count from this site (Hey, 1976, Table II) refers to a pebbly sand about one metre above this horizon and is still of the Baventian-Westleton type, with more than 90% of flints. Above the shelly Crags of the Bramerton area, however, as noted by Funnell, Norton and West (1979, 516), are unfossiliferous gravels with abundant quartz and quartzite. These are at similar elevations (25-30 m O.D.) to the deposits elsewhere in the Norwich area which have been included in the Westland Green Gravels, and, though nowhere well exposed, appear to be of similar composition.

Thus, it appears that the first introduction of abundant far-travelled pebbles into Norfolk took place soon after than the arrival of Macoma balthica.

Summary of conclusions

Pebbles of chert, from the Yorkshire Jurassic, and of quartz and quartzite, probably from the Bunter of the Midlands, had already been introduced into East Anglia by Baventian times. There is no clear evidence for the introduction of any additional far-travelled material until, towards the end of the time corresponding to the cold Pre-Pastonian a Substage, additional supplies of quartz and quartzite pebbles arrived in Norfolk, together with pebbles of chert from the Lower Greensand of the Weald. It is thought that these were introduced by the earliest (Westland Green) Thames.

On grounds of composition and altitude, a correlation is suggested between unfossiliferous pebbly beds in central Norfolk and the Westleton Beds of S.E. Norfolk and N.E. Suffolk, themselves tentatively assigned to the Bramertonian Stage by Funnell, Norton and West (1979). This would imply a marine transgression at this time extending to parts of Norfolk now nearly 40 m above sea-level.

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COMPOSITION AND ORIGIN OF THETFORD MINERAL WATER

R. Raiswell* and M. Tranter*

Introduction

A recent comprehensive review of United Kingdom subsurface waters (Edmunds et al., 1969) distingushes three main types of water, classified according to their temperature and total dissolved solid (TD) content.

Discharge temperature exceeds average mean annual air temperature	THERMAL WATERS	Unconstrained range of TDS values
Discharge temperature does not exceed average mean annual air temperature	MINERAL WATERS	TDS = 1000 to 1000 000 mgl^{-1}
	BRINES	TDS > 100 000 mgl^{-1}

Many relatively dilute (TDS < mgl^{-1}), non-thermal waters lying outside this classification still achieve considerable national reputations for their therapeutic properties (e.g. those from Malvern, Ilkley, Tunbridge Wells) and have consequently attracted relatively recent investigation. However this has rarely been the case with the less-known, dilute spring waters. It is the purpose of this paper, firstly to present new analytical data for one of these lesser-known therapeutic springs at Thetford (Norfolk), and secondly, to discuss the chemical original of the spring water.

Locality and Sampling

The market town of Thetford lies approximately 50 km south-west of Norwich. The spring emerges in the rear garden of Spring House, a privately-owned residence created from the original spa facilities. Spring House is located on

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the eastern side of the town, off Spring Row, between the rivers Thet and Little Ouse.

In the locality of the spring, boulder clay covers Upper Cretaceous chalk of the Turonian stage, Holaster planus zone (Peake and Hancock, 1970). The depth to bedrock is uncertain, but it seems likely that the spring originates elsewhere than in the superficial deposits (see later). The spring has been drilled and cased and now serves as the water supply for a swimming pool. White and greenish-white encrustations occur on the casing.

Unfortunately the spring is not now free-flowing, and pumping facilities were unavailable. Attempts were made to draw fresh water into the casing by repeatedly discharging samples to waste, but this procedure is likely to be only partially successful, as the sample finally collected may contain a component which has chemically evolved due to prolonged contact with the atmosphere.

Methodology and Results

Sample pH was determined using an Orion 401 pH meter with a combination electrode, calibrated at pH 7 and 9.18 (20°C). There was little drift during measurement. Dissolved carbonate species were measured by titration with 0.01 molar HCl (Golterman and Clymo, 1969), firstly to the phenolpthalein endpoint (to determine CO_3^{2-} and OH^-) and secondly, to the BDH mixed indicator endpoint (to determine HCO_3^-). The first titre was negligible in the case of Thetford spring water. Sulphate was measured by a gravimetric procedure (Maxwell, 1968) involving precipitation as $BaSO_4$. The Mohr titration with $AgNO_3$ (Golterman and Clymo, 1969) was used to determine chloride. All the major cations (NA^+, K^+, Ca^{2+}, Mg^{2+}) were measured by atomic absorption and the data are summarised in Table 1. Analysis was completed within a few hours of collection.

Spring Water Composition and Origin

The water composition can be represented on triangular diagrams showing the relative proportions (expressed in equivalents) of both the cations and anions (Fig. 1 and 2). The dominant dissolved species are clearly Na^+, Ca^{2+}, HCO_3^- and Cl^-, although there is some evidence to suggest that significant concentrations of Fe^{2+} may also be present. There is an appreciable charge balance error, with insufficient cation equivalent ($\Sigma^+ = 4.67 \times 10^{-3}$ equivalents) to balance the anions ($\Sigma^- = 6.00 \times 10^{-3}$ equivalents). Analysis of the Thetford spring water by Accum (1819) indicates an Fe^{2+} concentration of 0.4×10^{-3} mol. l^{-1} (Table 2). Although there are differences between the present analysis and that of Accum (1819), an Fe^{2+} concentration of this approximate magnitude would reduce the charge balance error to reasonable proportions.

The triangular diagrams also show the average composition of rainwater (Garrels and Mackenzie, 1971) and the compositional variations expected in rainwater, whose cationic and anionic composition is altered by the incremental addition of dissolved calcium and carbonate. The trends in both cationic and anionic composition lie close to the plotted composition of Thetford spring water. It seems reasonable to conclude that the water has a meteoric origin, with the main post-precipitation influence being from the dissolution of calcium carbonate.

Although the triangular plots are a valuable way of representing possible compositional variations, they give no quantitative information about possible constraints on water composition. The nature of these contraints can be demonstrated by a brief consideration of mineral water reactions.

The weathering of rock minerals is controlled to a great extent by the rate of supply of hydrogen ions (Curtis, 1975), as illustrated below for the particular case of calcium carbonate.

$$CaCO_{3\,\text{solid}} + H^+_{\text{aq}} \longrightarrow Ca^{2+}_{\text{aq}} + HCO^-_{3\,\text{aq}}$$

This equation demonstrates a general principle of mineral water reactions, that minerals are susceptible to attack by hydrogen ions and, as a result, natural waters lose hydrogen ions and gain metal and bicarbonate ions during weathering reactions. The hydrogen ions consumed in weathering can be derived from four main sources; atmospheric CO_2, biogenic CO_2, biogenic organic acids and the oxidation of sulphide minerals. Carbon dioxide from the first two sources dissolves in water to give a series of dissolved species capable of

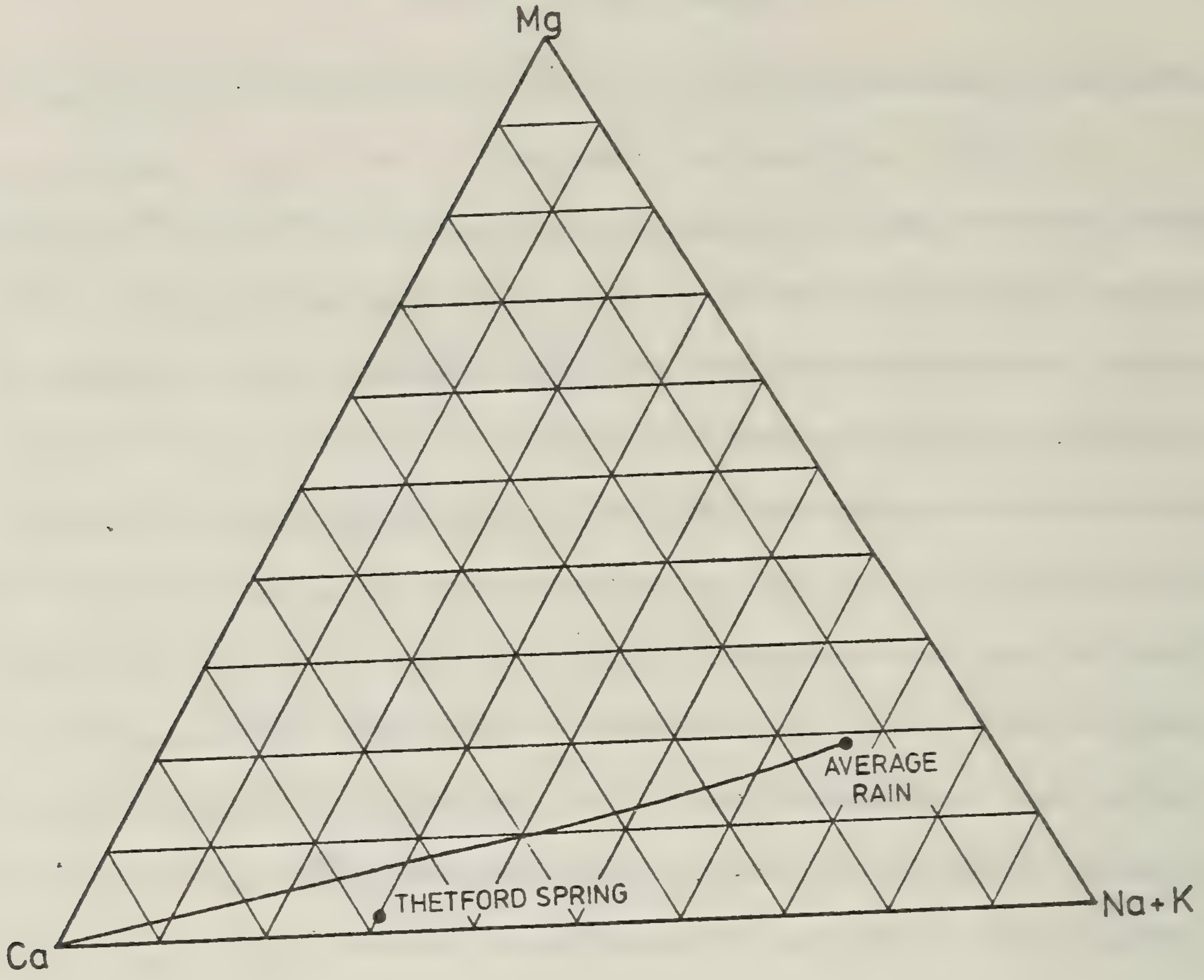

Fig. 1 The cationic composition of Thetford spring water, compared to the compositional variations which occur in average rainwater with increasing $CaCO_3$ dissolution. Cation proportions expressed as equivalents.

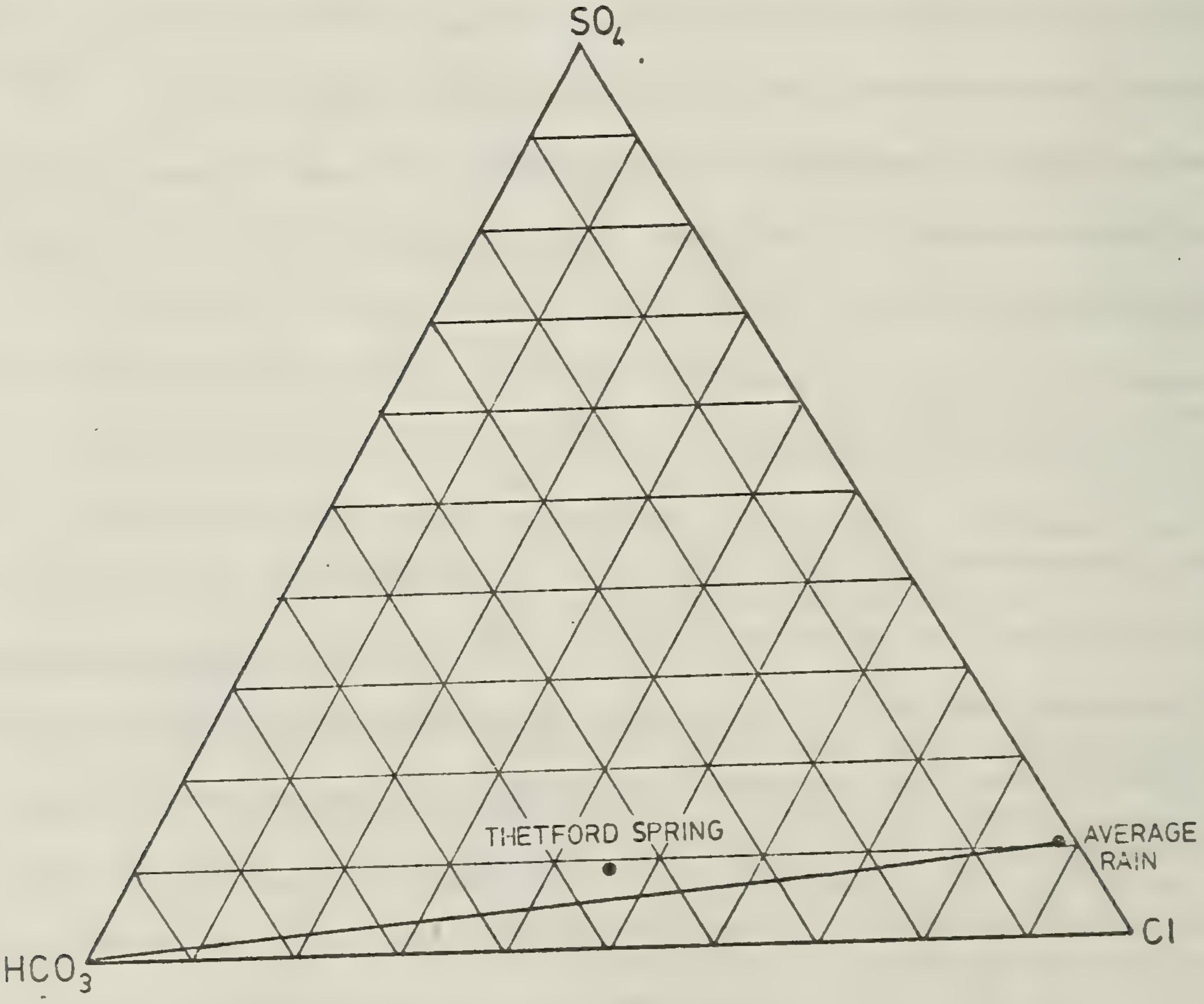

Fig. 2 The anionic composition of Thetford spring water, compared to the compositional variations which occur in average rainwater with increasing $CaCO_3$ dissolution. Anion proportions expressed as equivalents.

Table 1 Chemical composition of Thetford Mineral Water.

Cl^-	2.5×10^{-3}	$mol\ l^{-1}$
HCO^-_3	2.5×10^{-3}	
SO^{2-}_4	0.5×10^{-3}	
Ca^{2+}	1.6×10^{-3}	
Mg^{2+}	0.02×10^{-3}	
Na^+	1.3×10^{-3}	
K^+	0.13×10^{-3}	
pH	8.3	

Table 2 Comparisons with earlier analytical data.

	This work	Public Analyst	Accum (1819)	
Cl^-	2.5×10^{-3}	-	2.1×10^{-3}	$mol\ l^{-1}$
HCO^-_3	2.5×10^{-3}	-	-	
SO^{2-}_4	0.5×10^{-3}	-	0.5×10^{-3}	
Ca^{2+}	1.6×10^{-3}	2.8×10^{-3}	0.6×10^{-3}	
Mg^{2+}	0.02×10^{-3}	-	0.6×10^{-3}	
Na^+	1.3×10^{-3}	-	0.5×10^{-3}	
K^+	0.13×10^{-3}	-	-	
Fe^{2+}	-	-	0.4×10^{-3}	
pH	8.3	7.1	-	

dissociating in steps to produce hydrogen ions.

$$CO_{2\,gas} + H_2O_{liq.} \longrightarrow H_2CO_{3\,aq}$$

$$H_2CO_{3\,aq} \longrightarrow H^+_{aq} + HCO^-_{3\,aq}$$

$$HCO^-_{3\,aq} \longrightarrow H^+_{aq} + CO^{2-}_{3\,aq}$$

The ubiquitous presence of atmospheric CO_2 in surface environments, augmented in soils by the production of biogenic CO_2 from the oxidation of organic matter, indicates that in many cases carbon dioxide dissolution provides most of the hydrogen ions used in weathering reactions. The production of hydrogen ions from sulphide mineral exidation

$$3FeS_{2\,solid} + 15O_{2\,gas} + 8H_2O_{liq.} \longrightarrow 2Fe_2O_{3\,solid} + 16H^+_{aq} + 8SO^{2-}_4$$

may exert an important, but localised, influence depending on the availability of sulphide minerals.

Another source of hydrogen ions may arise from the dissolution and dissociation of organic acids, produced within the soil system by the microbiological degradation of organic matter. However, the high molecular weight humic and fulvic acids promote mineral dissolution by complexation and only the low molecular weight carboxylic acids are effectively dissociated to supply hydrogen ions. Such carboxylic acids constitute only a small proportion of the total organic acids present in soils systems (Yariv and Cross, 1979) and their contribution to soil acidity can often be ignored. Where sulphides and organic acids are negligible or absent, hydrogen ions can only be supplied by the stepwise dissociation of dissolved carbonate species, as described below.

A careful study of the stepwise dissociation reactions shows that the continued production of hydrogen ions used in weathering must result in the formation of progressively more CO^{2-}_3, since this is the final dissociation product. Hence the dissolution of $CaCO_3$ in water containing CO_2 results in dissolved carbonate species (HCO^-_3 and CO^{2-}_3) being formed from two different sources.

$CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons H^+ + HCO_3^- \rightleftharpoons 2H^+ + CO_3^{2-}$ HCO_3^- and CO_3^{2-} formed from CO_2

$CaCO_3 + H^+ \rightleftharpoons Ca^{2+} + HCO_3^- \rightleftharpoons Ca^{2+} + H^+ + CO_3^{2-}$ HCO_3^- and CO_3^{2-} formed from $CaCO_3$.

Thus dissolved carbonate species (HCO_3^- and CO_3^{2-}), the relative proportions of which depend on pH, are contributed to the solution from both the original CO_2 and $CaCO_3$. This dual contribution is important because the solubility of $CaCO_3$ has a theoretical maximum value, known as the solubility product (5×10^{-9} for $CaCO_3$ at 25°C and 1 atmosphere pressure). Thus we can define the saturation level for any given water as the ratio between the observed concentrations of Ca^{2+} and CO_3^{2-} in the water and the solubility product, as shown below.

$$\text{Saturation level} = \frac{(Ca^{2+})_{water} \times (CO_3^{2-})_{water}}{\text{Solubility Product}}$$

The significance of the saturation level is that it provides an indication of water behaviour with respect to $CaCO_3$; where the saturation level is less than unity, a water has the potential to dissolve more $CaCO_3$; where the saturation level is greater than unity, then precipitation of $CaCO_3$ should occur. Knowledge of the saturation level thus enables the direction of mineral water reaction to be predicted and the occurrence of dissolution or precipitation to be recognised. Quantitative estimates of the saturation level are however difficult, since account must be made for all the separate dissociation reactions which can occur. The relevant equations and procedures for their solution are given in Garrels and Christ (1965). Solutions can be derived manually but there are now a number of computer programmes available, which use measured analytical data (e.g. Ca^{2+}, pH, $HCO_3^- + CO_3^{2-}$ in the case of the Thetford spring water) to solve a series of simultaneous equations for the separate dissociation reactions. Use of one such programme (WATSPEC; Wigley, 1977) demonstrates that the Thetford spring water has a saturation level of 3.5 with respect to $CaCO_3$. Precipitation of $CaCO_3$ is to be expected and was found to occur in water samples standing overnight. It also seems probable that the encrustations observed on the spring casing consist predominantly of $CaCO_3$.

A further important feature of the WATSPEC programme is that an estimate can be made of the CO_2 content of the gas phase in contact with the water. In the open atmosphere CO_2 exerts a pressure equivalent to 0.03% of the atmosphere, but the Thetford spring water has experienced rather higher CO_2 pressures equivalent to 0.064% of atmospheric. The principal source of this excess CO_2 is probably from biogenic activity, resulting from the oxidation of soil organic matter to CO_2. Clearly the composition of Thetford spring water is determined by reactions in the superficial deposits, where organic matter is available, rather than in the bedrock. Enhanced concentrations of CO_2 produced from soil organic matter are dissolved to produce hydrogen ions, which are in turn used to dissolve $CaCO_3$ from residual chalk in the superficial deposits. On contact with the atmosphere, the spring water lose their excess CO_2 by degassing to the atmosphere, and in so doing, the dissociation reactions are reversed. The consequent removal of hydrogen ions results in the precipitation of $CaCO_3$, as the equation given below moves to the right.

$$Ca^{2+}_{aq} + 2HCO^{-}_{3\,aq} \longrightarrow CaCO_{3\,solid} + CO_{2\,gas} + H_2O_{liq.}$$

Compositional Variations

Some further conclusions can be drawn from a comparison between the analyses of Thetford spring water by Accum (1819) and by the Public Analyst's Laboratory (Table 2). The anionic components Cl^- and SO_4^{2-} determined by Accum (1819) are generally similar to those found in the present paper but there are significant differences in the cations, mainly Ca^{2+} and to a lesser extent, Mg^{2+} and Na^+. These differences could be attributed to inaccuracies in the old analytical procedures. However, the analyses of Ca^{2+} and pH by the Public Analyst are sufficiently reliable, and different from, the other analytical data, to suggest an alternative explanation. In this respect it is significant that the largest differences in the analytical data occurs in those species (Ca^{2+}, H^+) which are directly involved in $CaCO_3$ dissolution and precipitation. Analogous variations in the chemistry of spring and soil waters on chalk have been observed to occur seasonally (Pitman, 1978) due to variations in the CO_2 content of the soil gases (caused by variations in the rates of oxidation of soil organic matter). Soil gases reached their maximum CO_2 content in September and October and the soil waters were then characterised by low pH and high Ca^{2+} concentrations. Conversely, when the soil CO_2 is a minimum, pH is high and Ca^{2+} concentrations are low. The directions of these changes in pH and Ca^{2+} are the same as those found in a comparison of the analyses in Table 2. It seems reasonable to suggest that the chemical composition of the Thetford spring shows seasonal variations, analogous to those found in other Chalk springs. Unfortunately the data of Accum (1819) and the Public Analyst do not record sampling dates and regular monitoring of spring composition would be required to establish the existence of seasonal variations and their precise nature and magnitude.

It is unfortunate that the present data did not include analysis of Fe^{2+}, although this is a major cationic component in the data of Accum (1819). Dissolved iron was certainly present in the water analysed, becuse the precipitate of $CaCO_3$ which occurred on standing was stained red-brown by hydrated iron oxides. Iron is readily reduced and complexed during microbiologically-induced reactions with organic matter (Yariv and Cross, 1979) and its occurrence as a major constituent would suggest that organic acids played a lesser, but still significant role in the evolution of the Thetford spring water.

Conclusions

The composition of the Thetford spring water is determined by reactions between rainwater and residual $CaCO_3$ in the soil zone. The dissolution of $CaCO_3$ is caused by the generation of CO_2 from the oxidation of organic matter in the soil profile, possibly assisted by the formation and dissociation of organic acids. The soil gases consequently contain a greater proportion of CO_2 than does the atmosphere. The extent of $CaCO_3$ dissolution is dependent on the seasonally-variable production of CO_2 in the soil profile and significant temporal variations in spring chemistry are to be expected. On contact with the atmosphere, the spring water loses CO_2 by degassing and becomes over-saturated with $CaCO_3$, leading to the precipitation of $CaCO_3$.

Acknowledgements

The authors thank Mr. & Mrs. Hobbs, of Spring House, for permission to sample the Thetford spring.

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REPORT ON A FIELD MEETING TO BULCAMP, NEAR BLYTHBURGH, SUFFOLK, JULY 21ST 1979

P. G. Cambridge*

The coastal sections in the Lower Pleistocene Crags of Suffolk have been examined and described in detail by various authors. The Crags have also been examined in boreholes to the west, but no recent work has been done in the intervening area. For this reason it was decided to attempt to excavate a section in the Blyth valley.

A search of the literature suggested that an old pit near Union Farm, Bulcamp, might be suitable. The only published description appeared to be that of Prestwich (Proc. Geol. Soc. 1868). It was brief, litte more than a list of 28 species collected, a rough sketch of a section about 20 feet high (indicating considerable current activity), and a mention of the reddish colour of the sands giving a superficial resemblance to the Red Crag.

A preliminary examination of the site showed typical shelly Crag thrown out by rabbits, although the section itself was obscured. The large, partly degraded pit was easily accessible and it was decided to attempt to get part of the site cleared mechanically. Thanks to generous support from several sources this was possible and the day before the meeting a JCB digger started work, and was also present for part of the following morning.

A number of members of the Ipswich Geological Group joined us, enjoying excellent weather and really attractive surroundings. Part of the old face of the pit was re-dug, exposing a linear section, and a narrower trench was dug just to the west of this, exposing over two metres of shelly sands. The digger then made a trial hole at the lowest part of the trench, starting at the approximate level of the old base of the pit, to the full length of the digger arm, a depth of 2.8 metres, at which point the sand was still dry. After examination this hole was refilled for safety reasons but sections were left

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in the sides of the pit for further examination.

Most of the old pit was excavated in very shelly sand and the apparently unfossiliferous sands below were not used. Had the requirement been for sand and gravel these could have been dug at a higher level above the Crag so it is assumed that the shelly material was deliberately sought, probably as a source of lime for local agriculture.

Members were able to make comprehensive collections and bulk samples were taken by several members for further study. The pit was subsequently surveyed by levelling and has since been sampled as part of a study of the small mammal remains of the Icenian. The meeting demonstrated the value of using a digger and, providing funds can be raised, it is hoped that some other important sites can be excavated in the same manner. The larger excavations which can be made not only make investigation easier at the time but it is possible to leave a section which will be usable for a considerable time afterwards. It also allows trial holes to be quickly made and refilled, extending the scope of the work. The importance of the stratigraphical information gained at Bulcamp has yet to be assessed, but the fauna is being intensively studied and an important collection of small mammal remains has been made, including two genera new to the Norwich Crag. It is intended that a fuller description of the Bulcamp small mammals will be published elsewhere.

Thanks are due to a number of persons who made the meeting possible: to Capt. J.E.B. Hill, the owner of the land and his agent Mr. B.W. Candler, for permission to excavate and investigate the site; to the digger driver, Mr. N.C.A. Berry, for very skillful and helpful operation of the machine; to Messrs. H.D. Collins and R.J. Winyard for carrying out the preliminary surveys and negotiations and to Messrs. W. Corbett and J. Shields for carrying out the levelling survey.

The cost of £50 was met by grants from the Micropalaeontological Society and the Norfolk Research Committee and from contributions by Dr. P. Long of Leicester and J.M. Moraal of Vlissingen, The Netherlands.

NOTE: The Bulcamp site is on private property and permission is required for visits.

SECRETARY'S REPORT FOR 1980 - 1981

Unlike last year there were no casualties in this session of winter lecture meetins, although due to organisational problems the first one was not until November. We were able to cover a wide range of subjects, and the meetings were:

November, Mr. P.J. Lawrence, 'Trilobites Ruled OK'
December, Mr. C.E. Ranson, 'Wind Blown Deposits in East Anglia'
January, Professor I.G. Gass, 'Volcanism and Plate Tectonics'
February, 'Current Research in Geology at the University of East Anglia, short talks by UEA researchers; also in February, the Presidential Address by Mr. N.B. Peake, 'The Paramoudra and Other Flinty Problems',
March, Annual General Meeting.

The meeting addressed by Professor Gass was a joint meeting with the Norfolk and Norwich Geographical Association and was held at the Assembly Rooms. The Presidential Address was held at the Norfolk College of Arts and Technology, King's Lynn. Except for these two all meetings were held at the Castle Museum, Norwich. In addition a programme of meetings was organised by the West Norfolk Group and held at the Museum in King's Lynn.

There was one official and one *ad hoc* Committee Meeting held during the year.

From the Secretary's point of view the year proved a quiet one with only the delay in the production of the Bulletin causing any problems. Membership continues to grow, although attendance at meetings remains at about the same level.

The Treasurer asked me to remind members that annual subscriptions are due on the 1st January. There are still some people who have not changed their Bank Standing Order from the original October payment. The Secretary admits with some embarrassment that he was one of the out-of-step members. Would you also note that the current subscription is £2.00. Libraries and other Institutional members are invoiced when the Bulletin is sent out.

This year's Committee was:

Secretary : Dr. C. J. Aslin

Treasurer : Mr. P. G. Cambridge

Field Meeting Secretary : Mr. P. H. Lawrence

Editor : Dr. P. N. Chroston

Committee Members : Mr. D. J. Allen
Mrs. A. Horsfield
Mr. P. S. Whittlesea

West Norfolk Member : Mr. A. G. Barnes

Christopher J. Aslin
December 1981.

FIELD MEETING SECRETARY'S REPORT 1981

Seven meetings were held this season, five of which were outside the county.

Our first meeting on May 3 was to Cambridgeshire. The party of twenty-five members assembled at Rosslyn Pit, Ely, and proceeded to examine the Kimmeridge Clay sediments exposed at one end of the pit. Most members managed to collect some of the commoner fossils, especially small oysters and flattened ammonites. A few were lucky enough to find large ammonite aptychi. Discussion centred on the origin of the large septarian nodules which litter the floor of the pit. Following lunch, taken in Ely, the party travelled south towards Cambridge, to rendevous at the Corallian Limestone quarry at Dimmock's Cote near Wicken. This pit, always popular with the fossil collectors amongst our members, proved particularly prolific on this occasion. Hundreds of small sea urchins were picked up, particularly examples of Nucleolites and Holectypus. In mid-afternoon the meeting was prematurely brought to a close by a heavy cloudburst. This meeting was led by the Field Secretary.

In late May (24) the Field Meeting Secretary led a trip to the Norfolk coast at Eccles, in the hope of members finding some 'Forest Bed' fossils which had been turning up regularly over the previous twelve months. Twenty-four members assembled at the car park at Eccles only to find that the expected fossil rich stone beds were not exposed. Members busied themselves collecting off the beach instead. Slabs of iron impregnated clay containing leaf impressions, pine cones and mussels (of presumed Forest Bed age) were found by some members as well as sparse and rather water worn fragments of elephant bone. After lunch taken locally, it was decided to try our luck at another notable Forest Bed fossil locality, Sidestrand Beach. Here the tides were somewhat kinder, and several hundred yards of both stone bed and chalk platform were exposed. Several pieces of bone were picked up by members, including a fine cannon-bone (metapodial) of a horse, and, a large fragment of elephant bone. The chalk platform was particularly rich in large sea urchins (Echinocorys).

On June 7 the Society held a meeting to look at the classic 'Charnwood Forest' sections near Leicester. This meeting was arranged and led by Andrew England of Kings Lynn College. Thirteen members (all from West Norfolk) made the long trip and enjoyed a day looking at pre-Cambrian igneous and sedimentary rocks of the Charnian Series, as well as the Triassic sandstone which buried this ancient landscape.

Later on in June (28) the Society held its now annual (and very popular) joint field meeting with the Ipswich Geological Group. These "Crag digs" always attract most members, all confident of returning home laden with innumerable Crag fossils. Some twenty odd Norfolk members travelled down to Ramsholt Quay to meet up with another twenty or so Suffolk members and our leader for the day, Bob Markham of Ipswich Museum. The convoy of cars proceeded to our first collecting locality, the old disused pit at Alderton (in the Red Crag) Here a party was joined by one or two late-comers, swelling the numbers present to 49 individuals (a record for any one meeting). With members jostling for space along the one remaining face of the pit, collecting began in earnest. Soon everybody had found at least one prized sea-urchin (the tiny crag Echinocyamus pusillus (Müller)). Bivalves, gastropods and fragments of barnacles were particularly abundant and the lucky few found rolled and highly polished bits of rays' teeth and the very occasional shark's tooth. With promises from Mr. Markham of 'lots of sharks' teeth', later the party rather reluctantly left the fact and returned to their cars. Lunch was taken on the side of Sutton Knoll, a small hill formed by an outlier of Coralline Crag. Out first stop after lunch was a small pit in the Coralline Crag Rock Bed cust into the hillside above the river Deben. Here members collected typical Coralline Crag polyzoa and shell fragments. The party then moved off in the direction of the river towards the Ramsholt Cliff section, along the riverside path and enjoyed views of the local bird life. The beach at Ramsholt stood up to everybody's expectations of being an excellent collecting locality. Almost everybody collected some sharks' teeth which had been washed out of the Crag beds. Several large teeth turned up as well as a number of rays' teeth.

On July 5 the Society held a meeting at an opencast coal mine in Nottinghamshire. Twenty-five members left Kings Lynn by coach for the long journey to Nottingham. On route the party took an opportunity to view the changing geology and scenery as we traversed an almost complete section through the Mesozoic. The Marlstone ridge and Vale of Bevoir were topics of conversation en route. Our destination, Ryefield Colliery, Denby, WNW of Nottingham was reached by late morning. Here we were met by representatives of the Coal Board (regional geologist and the site civil engineer). Following a brief introduction to the site, the party left by coach for a conducted tour of the pit. On route, old air shafts were pointed out, as well as recent land reclamation schemes. On reaching the actual working faces the party was treated to an excellent talk on the current theories regarding coal formation by the resident regional geologist. The party then proceeded to walk to one of the lower working levels of the pit, passing a well defined fault in one rock face. At the lowest working seam (visible in both two and three dimensions) members took an opportunity to collect plant fossils (Sigillaria and Lepidodendron), as well as coal with pyrites. Several large complete stems were clearly visible on the upper surface of the coal seam. The party then moved on to the middle seam, an old previously underground working exposed by the opencast mining. Members collected excellent three dimensional plant fossils and rare freshwater bivalves on route. Primitive mining methods such as adits and 'bell'pits were carefully explained by the site engineer, and members were able to see original pit props in the side of the coat face being worked. The party then returned to the coach for a question session on route back to the main offices. On the way back from Nottingham to Kings Lynn a short unscheduled stop was made at a small quarry in the Lincolnshire Limestone near Donington. Here some of the party collected corals, bivalves and brachipods.

The penultimate filed meeting of the season in late July (26) was to study and collect from several quarries in the Lincolnshire Limestone. A small party of twelve members led by the Field Secretary started the dat at the large working quarry at Leadenham south of Lincoln. Here the Lower Lincolnshire Limestone is worked for limestone aggregate. Some beds proved to be particularly fossiliferous and members were able to collect good examples of the bivalves Pinna and Pholadomya as well as brachiopods. After lunch the party paid a short visit to another working quarry in the Lincolnshire Limestone at nearby Metheringham. Returning south along Ermine Street the party paid a return visit (by request) to the classis Great Ponton beds south of Grantham. These highly fossiliferous Upper Lincolnshire Limestone beds produced hundreds of fine brachiopods, bivalves and occasional gastropods.

Our final trip of the field season was held on September 13. This was a meeting, led by our President, Mr. Norman Peake, to study Paramoudras and related phenomena at West Runton. Sixteen members arrived at West Runton beach car park, our ranks being temporarily swelled by a very large party of Norfolk Naturalists. Mr. Peake's considerable artistic talents (with a hammer on wet sands) were admirably demonstrated as the party was treated to a first class talk on flint formation, paramoudras, pogonophores and flint circles. Having been educated in all things flinty, the party set off along the beach to East Runton, examining almost every flint on the beach. Following lunch taken in East Runton, members re-assembled on the beach. Discussion took place on the large chalk erratics clearly visible in the cliffs. The the west of the slipway at West Runton the party examined and marvelled at numerous flint circles, some enclosing paramoudras in their centres. Finally it was agreed that the party should return home via Overstand cliffs where we were able to see a single larger paramoudra in longitudinal section in the cliffs by the new slipway.

In general this year's (1981) meetings were very well attended. Our average attendance figures for the season was 23.7, easily the highest over the past seven field seasons and double the 1980 average attendances. No clear pattern emerges as to the most popular meetings, but clearly Crag digs are always exceptionally well attended and as such will be put in future programmes Meetings outside the county, particularly the Cambridgeshire and Nottinghamshire meetings were well attended. It would appear that guaranteed highly fossiliferous sites help to attract members, e.g. Dimmocks Cote, as well as slightly unusual meetings such as the coal mine meeting. The Field Secretary will bear both in mind for future programmes. The use of a coach for the first time certainly appears to have been successful, and certainly popular with the car drivers amonst the party.

Could I take this opportunity of thanking our West Norfolk members for organising the Nottinghamshire and Charnwood meetings. Thanks also, to the leaders of the various meetings.

P. Lawrence

November 1981

EDITORIAL NOTE

The Bulletin of the Geological Society of Norfolk seeks to provide an opportunity for the publication of research papers, notes, or general articles which are relevant to the geology of Norfolk in particular, or to East Anglia geology in general. The Society is also prepared to consider articles of general geological interest for publication, but normally they will be expected to include some local relevance. There are no restrictions on subject matter (apart from regional significance) and no formal restriction on length. We welcome full length research papers, short notes, and correspondence. All papers are normally refereed.

Potential contributors should note that we prefer manuscripts to be submitted in typewritten copy, and it would be helpful if the style of the paper in terms of capitalization, underlining, punctuation etc., would conform strictly to those used in the Bulletin. The reference list is the author's responsibility alone and should be checked carefully.

Illustrations should be executed in thin dense black ink line. Thick lines, close stipple or patches of black should be avoided as these tend to spread in the printing process employed. Original illustrations should, before reproduction, fit into an area of 225 mm by 175 mm. Full use should be made of the second (horizontal) dimension which corresponds to the width of print on the page, but the first (vertical) dimension is an upper limit only. Reproduction of photographs is normally possible provided there is adequate contrast.

All measurements in the script and illustrations should be in metric units.

I am happy to answer any queries concerning the suitability of a paper or any other editorial matter.

P. N. Chroston,
Editor,
University of East Anglia,
School of Environmental Sciences,
Norwich, NR4 7TJ.

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BULLETIN of the GEOLOGICAL SOCIETY OF NORFOLK

No. 33 December 1983

Editor: B.M. Funnell, School of Environmental Sciences
University of East Anglia, NORWICH NR4 7TJ

Assistant Editor: P.G. Cambridge, 258 Bluebell Road, NORWICH NR4 7LW

EDITORIAL

With the publication of Bulletin No. 33 Brian Funnell takes over as Editor and Philip Cambridge as Assistant Editor. Papers intended for publication, comments and suggestions, may be addressed to either editor. We apologise for delays in publishing material submitted for the present Bulletin. The next Bulletin (No. 34) will be published in December 1984. Research papers, review articles, and introductory items more suitable for our amateur readership are all solicited, and should be sent to us as soon as possible.

We are very grateful to Neil Chroston, who saw Bulletin No. 33 through its early stages, for his editorship over the last six years, during which time he has successfully widened and enhanced the reputation of the Bulletin. We also acknowledge our continuing indebtedness to secretaries, cartographers and photographers of the School of Environmental Sciences for their assistance in producing the Bulletin.

Potential contributors should note that we prefer manuscripts to be submitted in typewritten copy if at all possible. It is most helpful if the style of the paper, in terms of capitalization, underlining, punctuation, etc., is made to conform strictly to those normally used in the Bulletin. All measurements should be given in metric units. The reference list is the author's responsibility and should always be carefully checked. All papers are normally refereed.

BRITISH MUSEUM
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Illustrations are important. They should be drawn with thin dense black ink lines. Thick lines, close stipple or patches of solid black should be avoided as these tend to spread in the printing process usually employed. Original illustrations should, before reproduction, fit into an area of 175 mm by 225 mm. Full use should be made of the first (horizontal) dimension, which corresponds to the width of print on the page, but the second (vertical) dimension is an upper limit only. Half-tone (photographic) plates can also be accepted, providing the originals exhibit adequate contrast, and when their use is warranted by the subject matter. (A number of plates are included in the present issue.)

Authors are reminded that the Bulletin of the Geological Society of Norfolk exists to publish research papers, notes or general articles relevant to the geology of East Anglia as a whole, and does not restrict consideration to articles concerning the geology of Norfolk alone.

Corrigendum

A short corrigendum to the article on Amino Acids by Davies, Funnell & Funnell in Bulletin No.32 appears on p.44 of this issue.

B.M. Funnell
P.G. Cambridge

Bull. geol. Soc. Norfolk, 33, 3-26

A FAUNAL CORRELATION OF THE HUNSTANTON RED ROCK WITH THE CONTEMPORANEOUS GAULT CLAY, AND ITS IMPLICATIONS FOR THE ENVIRONMENT OF DEPOSITION

Julian Andrews*

Abstract

This study outlines the stratigraphical succession of the micro and macro-faunal assemblages of the Hunstanton Red Rock and compares these successions with those already well defined for the more ubiquitous Gault Clay facies of the Middle/Upper Albian Stage (Lower Cretaceous), from the sequence at Copt Point, Folkestone (Price 1977 and Hart 1973).

The correlation established is used to infer the equivalent Albian ammonite subzones for the Hunstanton Red Rock, and its stratigraphical context in relation to the underlying Carstone and the overlying Chalk. Characteristics of the Red Rock depositional environment are also considered.

Field relationships of the Carstone, Red Rock and Chalk

The Carstone-Red Rock boundary is essentially a gradational contact. In some localities the actual boundary would be hard to detect if it were not for a bench like feature produced at the top of the Carstone, (presumably where storm waves have preferentially eroded the more fissured Red Rock). In such localities the junction can be placed by the exposure of a thin creamy white sand band 20-40 mm thick beneath the lowest Red Rock bed.

A more obvious distinction between the deposits is the increased hardness and red colour of the Red Rock, as opposed to the more friable brown Carstone. However, texture of the basal Red Rock and pebble content (Rastall 1930) are strikingly similar. There is no evidence of scour at the contact, suggesting that the boundary is conformable.

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The White Chalk-Red Rock boundary (also the Lower/Upper Cretaceous boundary) is a somewhat more complicated contact. It is sharp and irregular, the Upper Red Rock bed capped by a thin seam (20-50 mm) of deep red, highly ferruginous silt/clay, described by Whitaker et al. (1899) as 'red earth'. In most localities the junction is complicated by deeply red-stained ball structures or nodules projecting into the base of the White Chalk.

The top 0.3-0.4 m of the Red Rock, and the basal bed of the Chalk are both penetrated by prominent vertical and horizontal burrow structures. This factor, coupled with the textural similarity of the beds, suggests a similar environment of deposition.

Stratification and bedding within the Red Rock

Previous work on the Hunstanton Red Rock (Whitaker et al. 1899, Larwood 1951) has tended to subdivide the deposit into three sections based on texture. The basal 0.4 m is described as a soft marly deposit, deeply brick red in colour, also sparse in macrofauna. The central 0.6 m of the deposit is described as a tough, red nodular limestone with less siliceous input and abundant macrofauna. Finally the top 0.3 m is defined as a pale pink, hard nodular limestone, mottled white, highly calcareous and less abundant in macrofauna than the central section.

These divisions though correct, can be further subdivided, as shown in Fig. 1. The diagram shows the distinctions made: from (Base) HA, HB, HC, HD, HE, to HF (Top).

Bed HA is the same basal 0.4 m of marly deposit as described above. "Pebble" sizes range from microns to 6 mm diameter. The top 80 mm of the bed shows evidence of partially formed calcareous nodules, the nodular material more fine grained than the marly matrix. The basal 155 mm of this bed has a more uniform massive silty structure probably due to intense bioturbation.

Beds HB and HC are a subdivision of Whitaker's central 0.5 m. This section can be treated as a transition zone between the calcareous top portion and siliceous bottom portion of the deposit. Bed HB shows a relatively high clastic input (although less than HA). The largest pebbles are about 3-4 mm diameter.

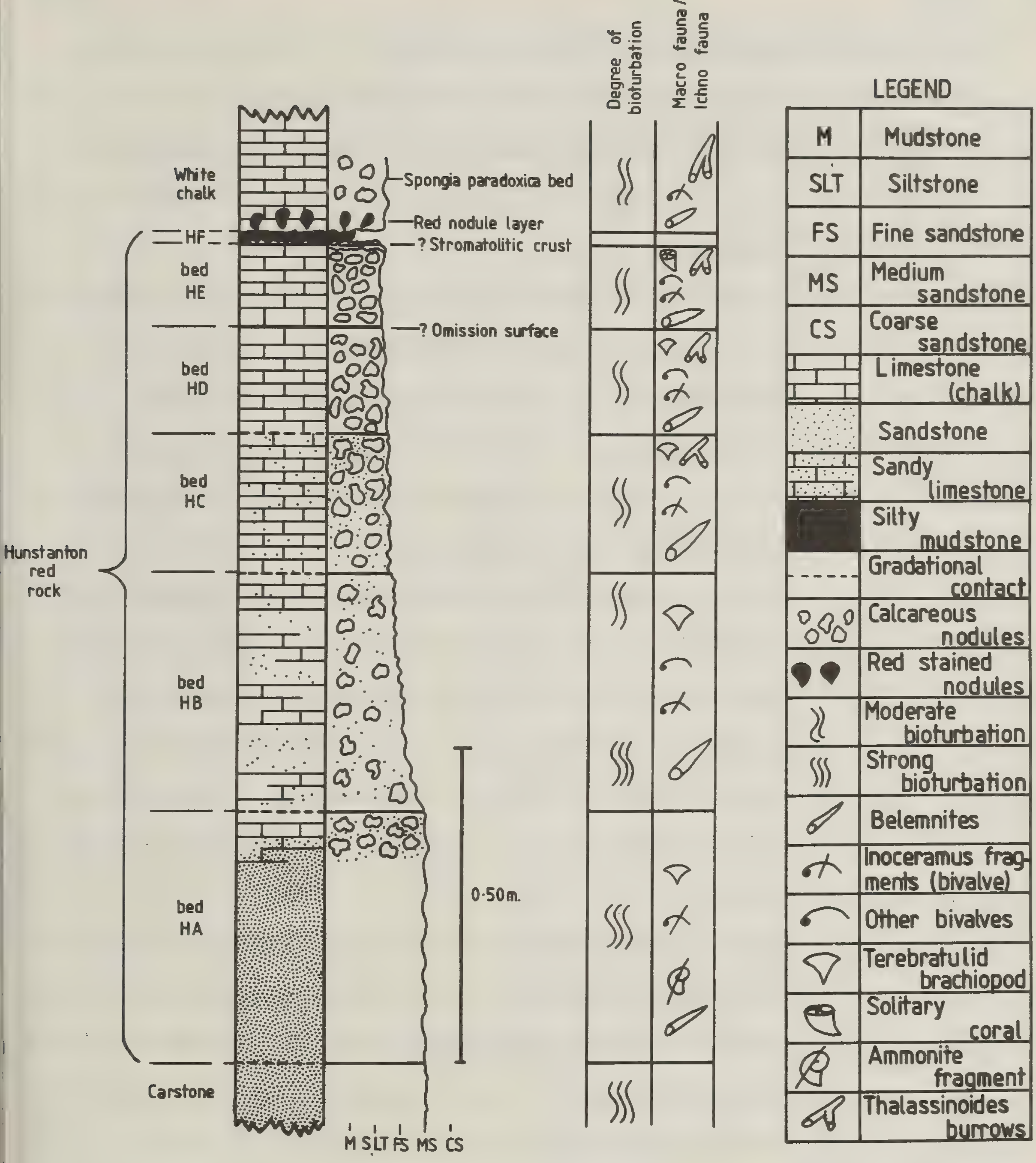

White chalk
HF
bed HE
bed HD
bed HC
bed HB
bed HA
Hunstanton red rock
Carstone
Spongia paradoxica bed
Red nodule layer
? Stromatolitic crust
? Omission surface
0·50m.
M SLT FS MS CS
Degree of bioturbation
Macro fauna / Ichno fauna
LEGEND
M Mudstone
SLT Siltstone
FS Fine sandstone
MS Medium sandstone
CS Coarse sandstone
Limestone (chalk)
Sandstone
Sandy limestone
Silty mudstone
Gradational contact
Calcareous nodules
Red stained nodules
Moderate bioturbation
Strong bioturbation
Belemnites
Inoceramus fragments (bivalve)
Other bivalves
Terebratulid brachiopod
Solitary coral
Ammonite fragment
Thalassinoides burrows

Fig. 1 Hunstanton Red Rock stratigraphic log

Calcareous nodules are more obvious than in HA and become increasingly well developed toward the top of the bed. Nodule boundaries generally grade into the marly matrix.

Bed HC appears somewhat harder and paler in colour. It is characterised by increasing nodularity toward the top. Nodule material is very fine micritic calcite, distinctly paler than the surrounding fabric. Nodule boundaries are quite definite. The top 50 mm of this bed shows evidence of burrow structures. Macrofauna is abundant in both these beds.

Beds HD and HE are similarly a subdivision of the upper section of Whitaker's threefold distinction. The junction between HD/HC is clearly defined by the highly nodular calcareous nature of HD, interspersed by burrow structures. (Vertical burrows are clearly evident in this bed.) Thin horizontal wavy laminations, deep red in colour about 1 mm thick are also visible. The deposit is harder than HC and macrofossils are less abundant.

The boundary between HD and HE is clearly marked by a sharp bedding feature (possibly an omission surface). HE is highly nodular, many of the order 30-40 mm longest axis. The nodules are pale pink mottled white (in thin section this material appears to be similar to the Chalk above); and surrounded by darker red structures, probably infilled burrows. The top of this bed has a relatively flat surface with a 1-2 mm thick crust capping it. This surface is in turn overlain by the red silt/clay, Bed HF.

Thin sections of Beds HD and HE, showed a remarkable similarity to the overlying Cenomanian Chalk with some Foraminifera, plus quite an abundance of calcispheres (often found in association with hard chalks, see Black 1980). I would agree with Hill (1899) who states: 'I should regard the upper two thirds of this bed (the Red Rock) as, lithologically, a real Chalk'.

The microfossil succession

Microfossils were examined from 23 samples, five from Bed HA, six from Bed HB, six from Bed HC, three from Bed HD, two from Bed HE and one from Bed HF. The samples were cut from the cliff section, measured from the datum of the White

Chalk "Spongia paradoxica" bed. After disaggregation the 63 µm - 1000 µm size fraction was analysed. At least fifty individuals were collected from each sample.

The microfaunal content of the Red Rock is not abundant, however there are sufficient significant foraminifers (plus a few ostracods) in each sample for zonation purposes. The successions of stratigraphically useful individuals is shown in Figs. 2 and 3.

Species of the Genus Hedbergella, Gavelinella and Arenobulimina are also tabulated as percentages of each species from the whole foraminifer population in the sample. First and last appearances of a given species are marked by the limit of the species bar; inferred presence of a species is marked by a pecked line. The species bars are plotted against the sample numbers HA1 to HF.

Discussion of the microfossil succession

This discussion makes direct comparisons with Hart (1973) and Price (1977), both successions from the Gault Clay at Folkestone.

By correlating first and last appearances of a given species from the Red Rock, with the two sources above, a comparison of the two Albian facies has been made, from which the equivalent ammonite subzones have been inferred, see Fig. 4.

Individuals found in Bed HA, are of Middle Albian forms. No Lower or Upper Albian forms are found in this bed. The first appearance of Gavelinella cf. baltica (Fig. 2) suggests the presence of the boundary between the Mojsisovicsia subdelaruei and Dimorphoplites niobe subzones; and the extinction of Arenobulimina macfadyeni between samples HA5 and HB1 defines the boundary between the Anahoplites daviesi and Diploceras cristatum subzones, which is also the Middle/ Upper Albian boundary. This result is interesting as it shows the significant Middle to Upper Albian boundary associated with the obvious boundary between Beds HA and HB. This result is thus important as it shows that only the basal 0.36 m (28%) of the Red Rock is of Middle Albian age. Thus the remaining 0.94 m (72%) of the sequence must be of Upper Albian age (assuming the Cenomanian begins at the base of the White Chalk). If existing literary sources are correct (Rawson et al.

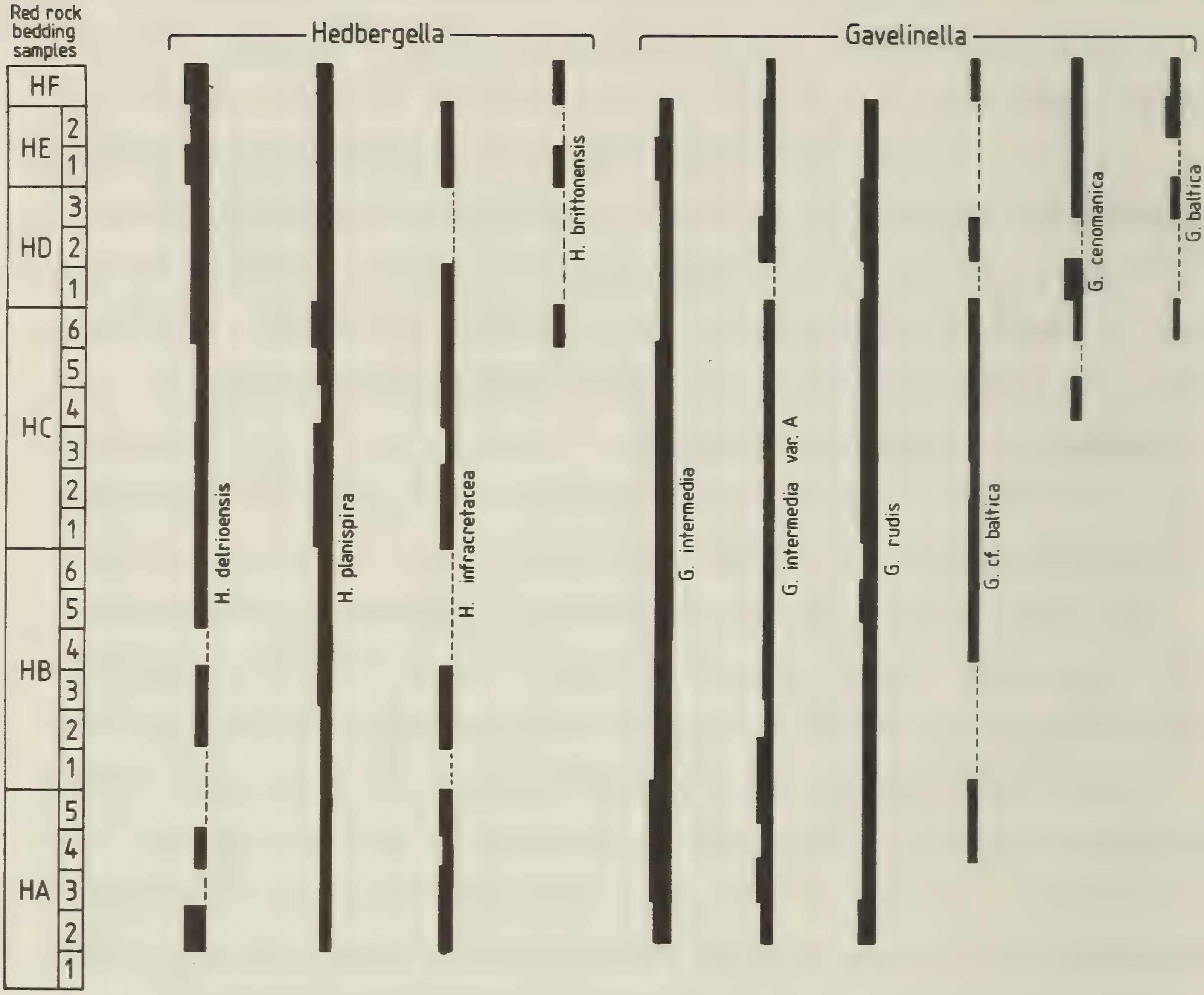


Fig. 2 Foraminifer succession

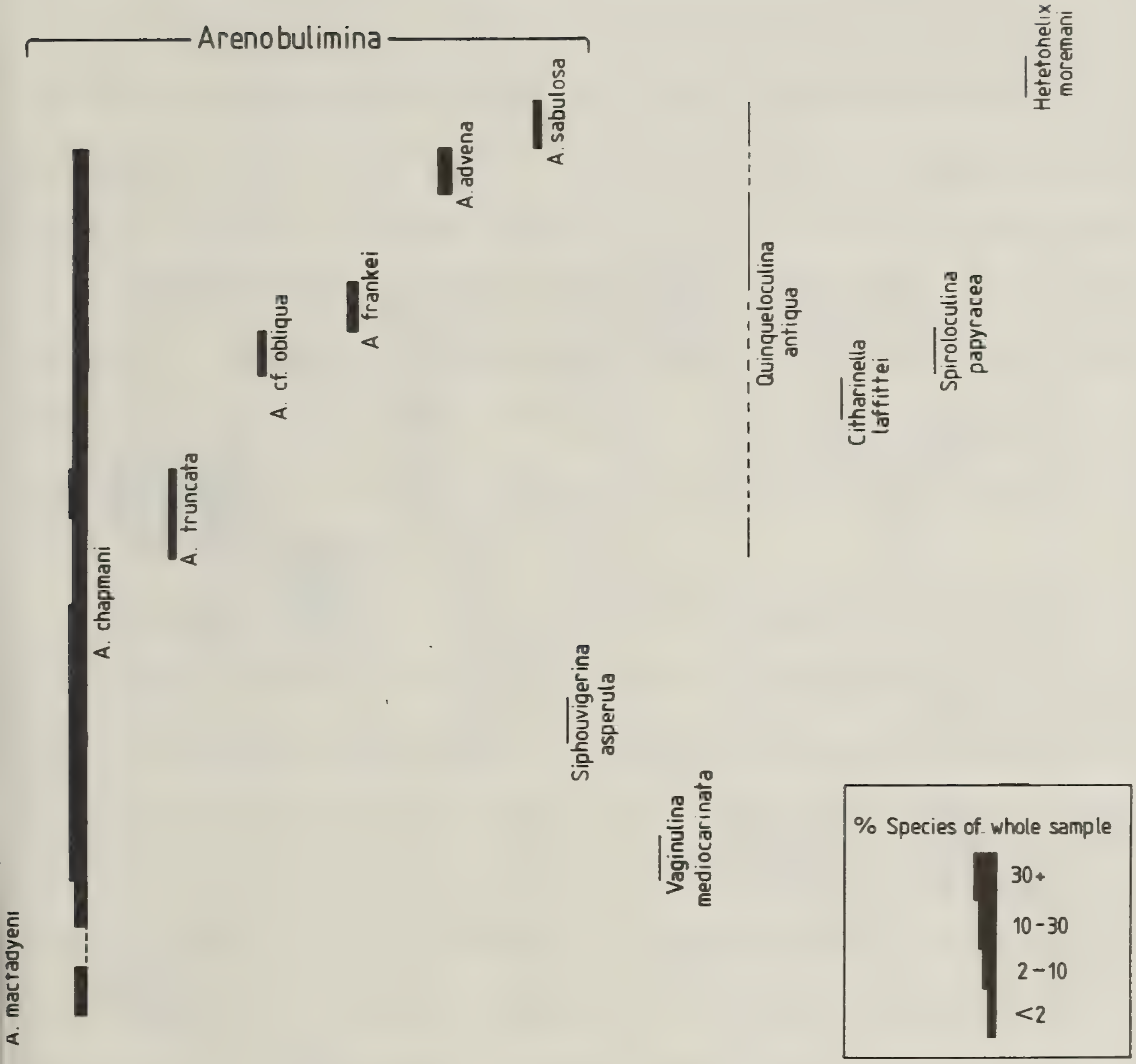


Fig. 2 (continued)

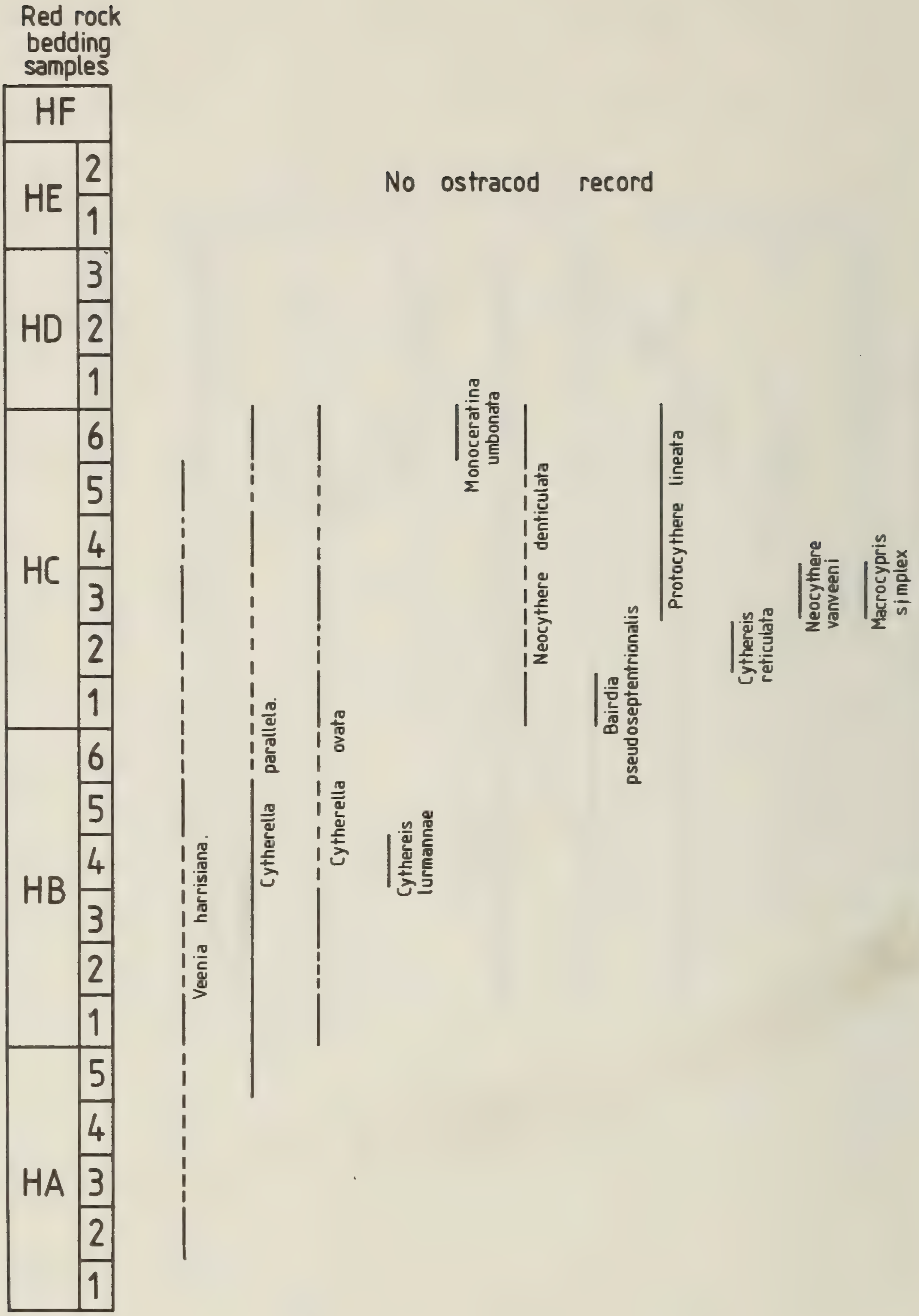


Fig. 3 Ostracod succession

1978), and the Carstone / Red Rock boundary is conformable (as the gradational contact would suggest), then the whole of Middle Albian sedimentation is represented by just 0.36 m of deposit.

Upper Albian indicators are somewhat better represented, especially by the presence of Arenobulimina chapmani, appearing in HB1 and continuing until HE1. Three definite subzonal indicators are present in the sequence. The first appearance of Gavelinella cenomanica in HC4 suggests the base of the Hystoceras varicosum subzone. Similarly, the first appearance of Hedbergella brittonensis suggests a position somewhere around the centre of the Callihoplites auritus subzone. The appearance of Arenobulimina advena in Bed HE1 (associated with the extinction of Arenobulimina chapmani) is important as it first appears in the Gault Clay succession (Price 1977) in the upper Stoliczkaia dispar zone (no macrofaunal subzone). This shows that most, if not all of the Upper Albian is present in the Hunstanton Red Rock.

Other data shown in Figs. 2 and 3 do not provide any further specific correlative evidence. However none of these species dispute the suggested boundaries except the presence of Vaginulina mediocarinata, which according to Hart's zonation, should appear from the base of the Hystoceras orbignyi subzone upward. In the Red Rock sequence it appears in sample HB1, which according to other species is in the Dipoloceras cristatum subzone. (It should appear in either HB3 or 4.) The explanation of this anomalous result is not easy, the distances involved, 50 mm at a minimum and 150 mm at a maximum do not suggest an overlap of samples. Adequate care was taken to avoid sample contamination and there is no satisfactory way to resolve the present observations with those of Hart (1973). However, this result on its own is insufficient to question an otherwise good correlation.

The ostracod succession produces no boundary markers but Upper and Middle Albian forms agree with the suggested succesion based on the foraminifers.

It should be noted that the succession shown in Fig. 4 is not suggested as absolutely representing the equivalent zonal scheme of the Gault Clay. (Obviously

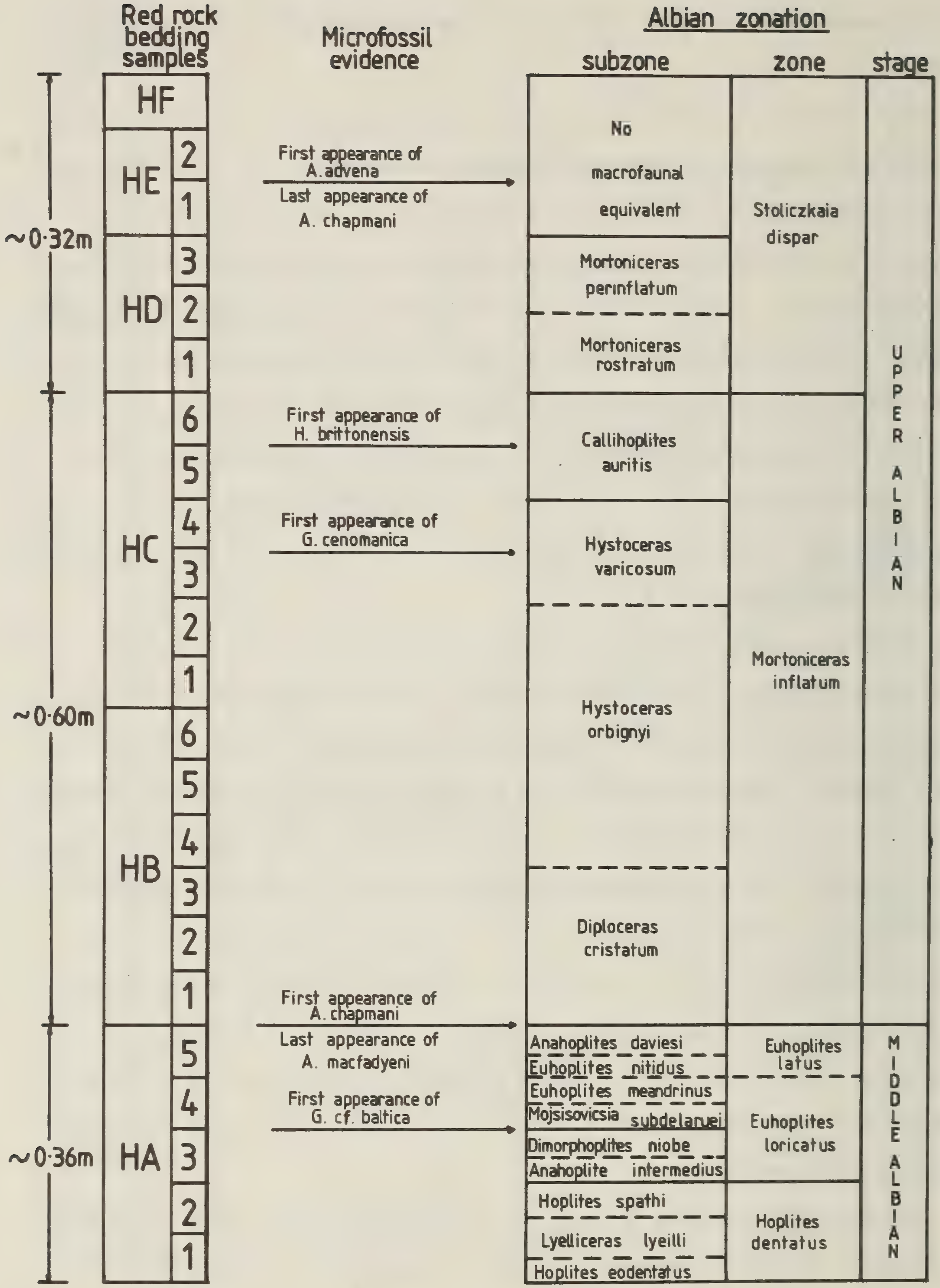

Red rock bedding samples
Microfossil evidence
Albian zonation
subzone
zone
stage
HF
HE 2 1
HD 3 2 1
HC 6 5 4 3 2 1
HB 6 5 4 3 2 1
HA 5 4 3 2 1
~0·32m
~0·60m
~0·36m
First appearance of A. advena
Last appearance of A. chapmani
First appearance of H. brittonensis
First appearance of G. cenomanica
First appearance of A. chapmani
Last appearance of A. macfadyeni
First appearance of G. cf. baltica
No macrofaunal equivalent
Mortoniceras perinflatum
Mortoniceras rostratum
Callihoplites auritis
Hystoceras varicosum
Hystoceras orbignyi
Diploceras cristatum
Anahoplites daviesi
Euhoplites nitidus
Euhoplites meandrinus
Mojsisovicsia subdelaruei
Dimorphoplites niobe
Anahoplite intermedius
Hoplites spathi
Lyelliceras lyeilli
Hoplites eodentatus
Stoliczkaia dispar
Mortoniceras inflatum
Euhoplites latus
Euhoplites loricatus
Hoplites dentatus
UPPER ALBIAN
MIDDLE ALBIAN

Fig. 4 Red Rock zonation based on Foraminifers

the Red Rock zones differ, e.g. the thickness of the Hystoceras orbignyi zone would suggest inaccuracy in correlation). However it is suggested that a broad comparison between the two facies is possible; at least it shows that most if not all the Upper Albian and probably all of the Middle Albian is represented by the Red Rock.

The percentages of Hedbergella, Gavelinella and Arenobulimina were calculated as a percentage of the total foraminifer population, in an attempt to correlate the figures with those of Price (1977), (the relative percentages between the two facies could have correlated). Generally, however they do not agree closely, possibly due to rather small sample sizes (of individuals) from the Red Rock (hence small numbers of any individual species have a more significant effect than in a larger sample). Moreover, the conditions limiting species populations between the two facies could be quite different. This data was not used for correlative purposes.

It should also be noted, that if the whole Middle to Upper Albian succession is represented by the Red Rock, then changes within its microfaunal sequence will be expressed very much more quickly and abruptly than the contemporaneous Gault Clay. Hence, even with a sample pattern of 50 mm intervals small errors in control could result in large correlative errors. For example, in the Middle Albian section at Hunstanton each 50 mm sample will encompass two subzones (if all present).

Finally it should be noted that some species in the Red Rock samples, notably Arenobulimina truncata, A. cf obliqua, A. frankei and A. sabulosa, did not produce continuous records of existence. This is probably due to their rarity as species, which are therefore easily missed in a small individual sample (especially as their presence is typically in the upper beds HD and HE, where disaggregation techniques were less effective).

The macrofaunal succession

The only Class useful for zonation purposes is the Belemnoidea. The succession is presented in Fig. 5, compared with a collection from the Albian of the Speeton section, Yorkshire (see Wright et al. 1955).

The Red Rock sequence shows three salient features. (1) Belemnites from Bed HA (Middle Albian) are rare and all individuals collected were of the species Neohibolites minimus var. oblongus. (2) The most abundant belemnite content was found in Beds HB and HC, which, from the microfossil succession, represents the Mortoniceras inflatum zone of the Upper Albian. Species include Neohibolites minimus (s.s) and variants submedius, oblongus and attenuatus. (3) Beds HD and HE, suggested as the Stoliczkaia dispar zone, are characterised by smaller belemnites, typically half the size of those in Beds HB and HC. The only species found in these beds were N. minimus (s.s). (It should be noted that Spath (1973) has shown some individuals thought to be N. minimus (s.s) are in fact N. ernsti. However, this difficult distinction has not been made.)

Fig. 5 shows that the correlation between the Speeton and Hunstanton succession is quite good. The Middle Albian sequence at Speeton A2 and Hunstanton HA suggest a relative abundance of N. minimus var. oblongus, although the Speeton collection has other related species. The Mortoniceras inflatum zone of each section shows a relative increase in the abundance of N. minimus (s.s) and this trend is even more pronounced in the Stoliczkaia dispar zone, although again associated species are found at Speeton in Bed W.

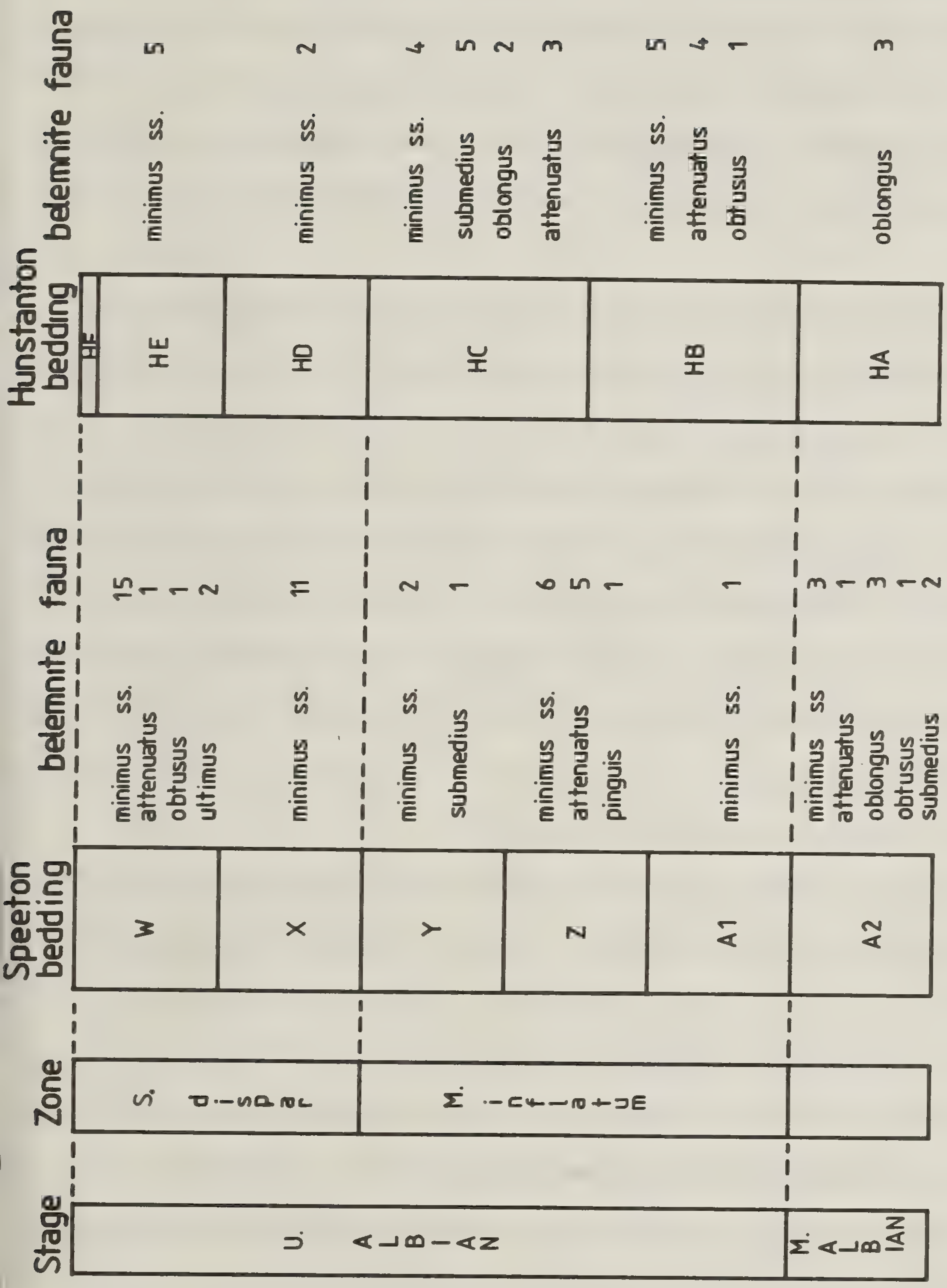
This correlation of belemnites agrees broadly with the microfossil zonation previously proposed. It supports the suggestion that Bed HA of the Red Rock is of Middle Albian age; that Beds HB and HC are the Mortoniceras inflatum zone of the Upper Albian and beds HD and HE/HF are the Stoliczkaia dispar zone of the Upper Albian.

With the results of this part of the study, we may now consider some of the sedimentary features of the Hunstanton Red Rock, in order to try and understand its formation and appearance.

Sedimentary features

The nodularity of the Red Rock

Anderton et al. (1979) and Hallam (1967) have remarked upon the similarity of the English Red Chalk (including the Hunstanton Red Rock) and other nodular


Stage
Zone
Speeton bedding
belemnite fauna
Hunstanton bedding
belemnite fauna
U. ALBIAN
M. ALBIAN
S. dispar
M. inflatum
W
X
Y
Z
A1
A2
minimus ss. 15
attenuatus 1
obtusus 1
ultimus 2
minimus ss. 11
minimus ss. 2
submedius 1
minimus ss. 6
attenuatus 5
pinguis 1
minimus ss. 1
minimus ss 3
attenuatus 1
oblongus 3
obtusus 1
submedius 2
HE'
HE
HD
HC
HB
HA
minimus ss. 5
minimus ss. 2
minimus ss. 4
submedius 5
oblongus 2
attenuatus 3
minimus ss. 5
attenuatus 4
obtusus 1
oblongus 3

All species listed above are variants of the belemnite Neohibolites minimus.

NB. This diagram is descriptive. Bedding shown has no time/thickness significance.

Fig. 5 Belemnite succession of the Hunstanton Red Rock, and comparison with the Speeton succession

limestones, notably the Ammonitico Rosso. Jenkyns (1974) describes some characteristics of this Tethyan Jurassic deposit and also suggests a diagenetic model. The Red Rock characteristics correlate well with this deposit, especially in that marly interstices around nodules are richer in fossils than the nodules, and that contacts between nodules and the marl matrix are often gradational.

Jenkyns' early diagenetic segregation model of nodule formation is worth mentioning as it suggests some physical and bathymetric parameters for the deposit.

The model suggests an early diagenetic migration of $CaCO_3$ from marly areas to loci of precipitation occurring just below the sediment/water interface. It is proposed that $CaCO_3$ from unstable aragonite and low magnesium calcite is supersaturated in the interstitial sediment fluid, resulting in the precipitation of the less stable polymorph around large calcite crystals of skeletal origin, or lime rich intraclasts. This model is well suited to the Red Rock as it requires slow sedimentation rates, less than 2 mm Ka^{-1}, to ensure that reactions relying on proximity to the sediment water interface occur to completion. The model is also able to account for rhythmic 'courses' of nodule precipitation which is probably poorly exhibited in the Hunstanton Red Rock.

An interesting rider to this theory in application to the Red Rock is also evident. The diffuse nature of the nodules in the lower Beds HA and HB may be explained by a relatively higher sedimentation rate, precluding the supply of HCO_3 and Ca^{2+} by increasing diffusion paths and inhibiting nodule maturity. Conversely, the upper Beds HD and HE exhibit more obvious nodule boundaries, suggesting a relatively slow sedimentation rate allowing full nodule development. If correct, the increasingly well developed nodules in the Red Rock accumulation suggest that sedimentation rates were slowing down, presumably associated with a transgressive phase and distance from sediment source. Finally the rates may have increased again with the red silt/clay layer HF; Rastall (1930) on the basis of mineralogy proposes that the source of this material is different to that of the lower Red Rock.

If we suppose that the period of Red Rock deposition, (Middle Albian to Upper Albian) was in the region of 6 million years (Ma), then this suggests a sedimentation rate in the order of 0.2m Ma^{-1}, a very slow rate, especially when compared to the Gault (at its maximum) around 13 m Ma^{-1} or the overlying Cenomanian, in the order of 10 m Ma^{-1}. The result would suggest that sediment supply and productivity of the waters were quite low, although condensation of the facies may accentuate this factor.

Burrow structures

As already stated, the Red Rock shows evidence of burrowing, especially in Beds HE and HD. Various authors have suggested these ramifying structures were rootlet beds or sponges (hence the name of the basal Cenomanian bed, "Spongia paradoxica"); however, modern interpretation (Bromley 1967) suggests convincingly that these are burrow networks of the decopod Crustacean, genus Thalassinoides (similar to modern shrimps). The descriptive features stated by Kennedy (1975) are adequate to describe the Red Rock burrows; vertical shafts connecting horizontal tunnel networks typically 10-15 mm diameter with Y-shaped branching patterns.

Various authors suggest that these burrow systems are found commonly in association with nodular limestones; indeed Bromley (1967) states, 'the presence of nodular chalk indicates the former existence of Crustacean burrows'. Kennedy (1975) provies a model for their appearance:

1. Decreased sediment supply produces stable sea floor upon with Arthropod colonies can establish.
2. About 100 mm below the sediment water interface local precipitation of calcitic concentrations begins.
3. Nodule growth inhibits burrowing and Thalassinid systems become highly irregular to avoid contact with growing nodules.
4. Changes in sedimentation supply may freeze this situation before a full hardground forms, hence the contorted burrow systems and nodules are lithified.

Finally in consideration of these structures, one should study their reliability as indicators of marine palaeodepths. Unfortunately Thalassinid Crustacea are poor bathymetric indicators unless the actual species can be identified. Various authors have attempted depth ranges but correlation is poor, e.g. maxima of 65 m, 100 m and 330 m. Conversely some species would almost definitely have been inhabitants of the littoral or shallow sub-littoral environment (by modern analogy). The only correspondence of these views being that the environment was of shelf sea type; relatively shallow waters probably not in excess of 500 m. This would seem to agree with the rather clastic nature of the sediment suggesting a near continental source.

The nature of the Chalk/Red Rock boundary

The problems posed by this contact are threefold: (1) the contact is sharp, (2) the colour of the Red Rock does not generally cross the definite boundary, and (3) in some localities nodular structures, colour-stained as in the Red Rock, apparently project into the basal 50 mm of the overlying White Chalk. The questions are therefore: why did the colour staining essentially stop at this boundary, and how can the nodules be explained? The latter problem will be explored first.

The nodules described appear usually as ball or tubular shaped structures, sometimes tapering slightly to their base, with the largest axis typically in the region of 5-50 mm length. As hand specimens give no clue to their formation, the structures were first examined in thin section. The most obvious feature noted in thin section was that the composition of the structures and surrounding Chalk was identical. Other than the colour difference, composition was similar, including Foraminifera, calcispheres and micritic calcite. This result was important, as it suggested that the structures were composed essentially of Chalk material, and that this material is of the same age as the surrounding matrix, (i.e. it has not come up from the Red Rock, as the underlying bed is HF the red silt/clay layer, of very different composition). This result thus suggests that the structures were formed under marine conditions and are not associated with sub-aerial conditions, such as a soil horizon.

The next step was to see if any textural difference could be distinguished under the Scanning Electron Microscope (S.E.M.) at high magnifications. Interestingly the sample showed very similar composition between nodule and surrounding Chalk at relatively low magnifications (x 22). However, at very high magnification (x 2000) it became apparent that there was a very slight difference between textures. The Chalk generally showed the grains tightly packed in plate-like arrangements, whereas the nodule had a more granular or open structure, i.e. the nodule could be described as a 'disturbed' variant of the Chalk. The problem remained to explain this feature.

The most obvious explanation of this disturbance, bearing in mind that it occurred under marine conditions, presumably penecontemporaneous with sediment deposition, is the action of burrowing infauna, reworking the unlithified sea floor. Evidence of burrowing is abundant both in the basal Chalk and Upper Red Bed; indeed the only separation between the two sets is the red silt/clay layer at the top of the Red Rock. Although no definite proof has been discovered, I suggest that a likely cause of formation of these 'nodular' structures is through the action of burrowing infauna. The following model attempts to account for this.

1. Near the end of Red Rock deposition (Bed HE) a slight scour may have planed the top of the sea floor, followed by a change in conditions, leading to the deposition of the red silt/clay.
2. This change in conditions was short lived and reverted to Chalk sediment in the Cenomanian, essentially a similar deposit to Bed HE of the Red Rock. Burrowing infauna were established, penetrating the soft sediment and presumably encountering Bed HF below. (Evidence as to whether penetration of Bed HF occurred is not available, for in no place on the Hunstanton section does Bed HF exist flush with the Chalk and Red Rock, i.e. the seam is eroded back by storm waves, hence the accessible front portion of the deposit is missing.) If this fauna did penetrate Bed HF, they could not have burrowed into Bed HF (hardground), unless they re-excavated the infilled burrows.

3. As Chalk accumulated above the Red Rock, at some given time the Red Rock became stained, presumably due to mobile forms of iron in solution. It would appear that this colouration could not pass the boundary of HF and the overlying Chalk, (presumably because the Chalk is essentially impermeable). However, it may be that it could pass into the basal burrow structures where faunal reworking had made the sediment more porous (as suggested by S.E.M. results), i.e. the colour was let into the White Chalk where infauna had breached the otherwise impermeable contact of the Chalk.

We can now briefly consider, in conjunction with this model, the colour change from the Red Rock to the Chalk. (It should be noted that this report does not try to explain the source of the red colouration, other than it is believed to come from below the Red Rock, i.e. from the Carstone, as a mobilised iron solution precipitated as the oxide.)

Firstly we must try to establish the reason for the cessation of the colour at the lithological boundary between the Chalk and Red Rock. The most obvious model to explain this is that there was a significant time break between Red Rock and Chalk deposition, during which the redness of the Albian deposit was established.

This possibility was investigated by study of the microfaunal content of the basal 50 mm of the Cenomanian bed. It was hoped to locate this sample on the Cenomanian successions of Hart *et al*. (1981) and Hart (1979), and hence establish whether a time break had occurred. Unfortunately no useful results were forthcoming. The Hunstanton sample yielded no distinctive basal Cenomanian forms such as *Globigerinelloides bentonensis*, *Rotalipora appeninica* or *R. greenhornensis*, but only species of *Hedbergella*, typically *H. delrioensis*, *H. planispira* and *H. brittonensis*, plus other stratigraphically uninformative benthonic forms. This result could not realistically be compared to the succession cited above, for although Hart shows that *Hedbergella* become dominant in the Upper Cenomanian, the correlation is unconvincing. The possibility that much of the Cenomanian is missing does not seem likely, (indeed no literature on the Hunstanton area suggests this is so). Thus the microfaunal evidence neither proves nor disproves the existence of a time break.

An attempt was also made to test the proposal of a time break by study of the clay mineral content of the red silt/clay band and compare results with the known clay mineral content of the Norfolk Chalk (Jeans 1968) via X-ray diffraction methods. However, the results were very similar and provided no evidence to justify a break in time between sedimentation of the two deposits.

With no evidence to support or deny a break in sedimentation at the top of the Red Rock, a slightly different model of colouration was considered. If colouration of the Red Rock occurred some time after sedimentation, presumably during Chalk deposition, then iron moving up sequence in pore waters from the Carstone, should produce a richer colouration in the basal Red Rock, as opposed to the upper beds. This result is borne out in the field, and this distribution of colour must be partly due to the porosity of the sediment at different localities, i.e. in the basal marly section porosity is relatively high and red colouration can easily penetrate the material. Conversely, as we progress up the section, the increasingly calcareous material is accompanied by a decrease in porosity. Hence much of the upper deposit is only partly stained (and colouration less intense), with most staining occurring in the burrows or matrix surrounding nodules, where bioturbation has kept porosity relatively high. However at the top of the deposit, the silt/clay seam with a higher porosity may have acted as a colour sink or 'sponge'. Moreover solutions trying to move past this bed would be prevented from doing so by the relatively impermeable nature of the Chalk. Only where burrow structures in the Chalk breach the Red Rock boundary can this solution escape upwards forming the red nodules. (In thin section it can be seen that the redness from these nodules does partly transgress into the Chalk, but fades quickly within 2-3 mm of the nodule boundary, suggesting a suddenly decreasing porosity.).

If a porosity model such as this was working, it could account quite neatly for the white/pale pink nodules of the Upper Red Rock, linking textural composition and colour. This theory has no laboratory or field proof, however I suggest that the model is not unreasonable in that it can realistically account for colouration features seen in the Red Rock.

Conclusions

Micro- and macrofaunal evidence show that the Red Rock of Hunstanton is of Middle to Upper Albian age, that it is conformable with the underlying Carstone, and probably conformable with the Chalk above. Broadly the Red Rock microfaunal succession is the same as the Gault Clay, showing that it is not an extensively reworked deposit. Sedimentologically the Red Rock represents a transitional bed between sandstone deposition (as in the Carstone) and true Chalk.

Sedimentary features and associations of the Red Rock are also used to suggest a sequential depositional history for the Hunstanton area during the Aptian-Cenomanian period. During Late Aptian/Early Albian stage the Carstone was deposited, presumably as a shallow shelf sandstone within depths of effective wave action (indicated by cross-bedding). Proceeding through the Middle/Upper Albian, as water depths increased (no tidal or current features are seen in the Red Rock) clastic supply was limited and a generally more calcareous deposit formed (essentially Chalk deposition in the upper Red Rock). This shallow shelf carbonate of the Cretaceous Northern Province was presumably connected to the Southern 'Wessex' Basin by a seaway (Anderton et al. 1979), hence the similar distribution of microfauna and the correlation of successions between Hunstanton and Folkestone. With continued sea level rise in the Upper Cretaceous Chalk deposition dominated the area.

Acknowledgements

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Note (added July 1983)

Since completion of work for this paper (Autumn 1980), two important publications have added to knowledge of the East Anglian Albian deposits.

Wilkinson and Morter (1981) produced a biostratigraphical zonation of the Gault Clay based on Ostracods in boreholes at Gayton, Marham and Mundford, approximately 22, 32 and 45 km SSE of Hunstanton respectively. Their results suggest that the age of the Gault extends from the dentatus ammonite zone, (lyelli subzone) to the dispar ammonite zone, (rostratum subzone). This result agrees with my correlation although the appearance of Arenobulimina advena suggests the top of the Red Rock is slightly younger than the top of the East Anglian Gault. Moreover their work demonstrates that certain subzones are missing within the Gault sequence. This is almost certainly also the case with the Red Rock, but the condensed nature of the deposit and occurrence of omission surfaces makes subzone identification very difficult.

Jeans (1980, p.108-113) discusses the nature of the Red Rock/Chalk boundary at Hunstanton. He interprets the 'crust' feature at the top of the Bed HE as an algal stromatolite, and the red nodules projecting into the Chalk as algal columns. On subsequent trips to the Hunstantion section, I would agree that some of the structures may be stromatolitic, however I am as yet unconvinced that the red nodules are of algal origin.

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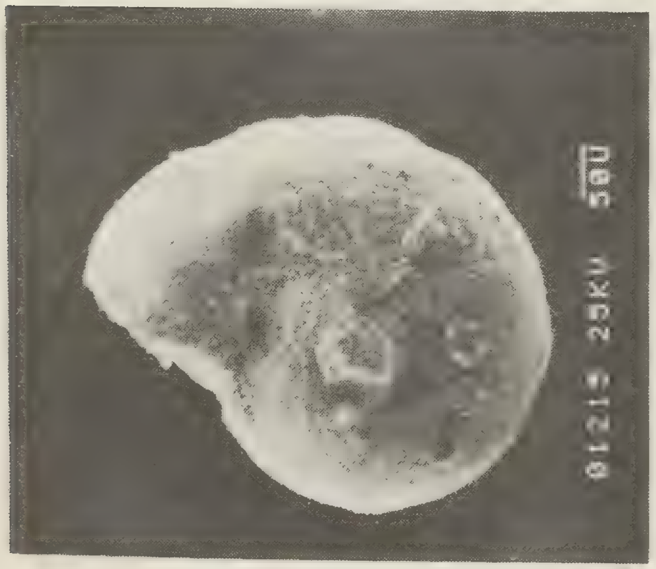
Draft received September 1981; revised and Note added July 1983.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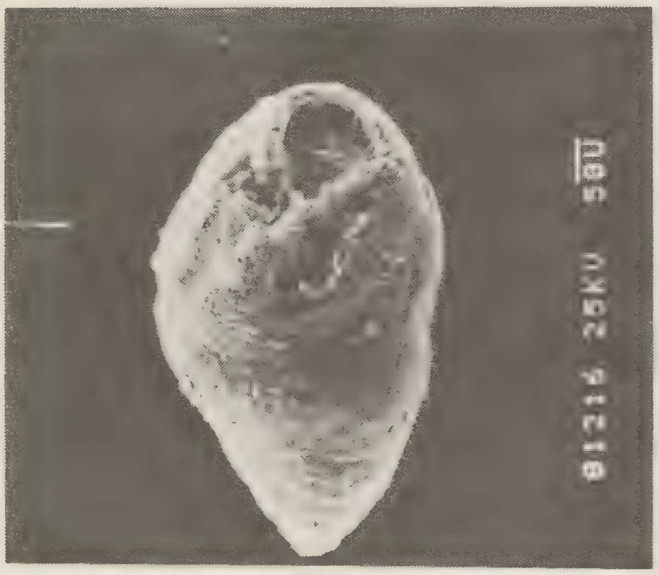
Gavelinella cenomanica (Brotzen)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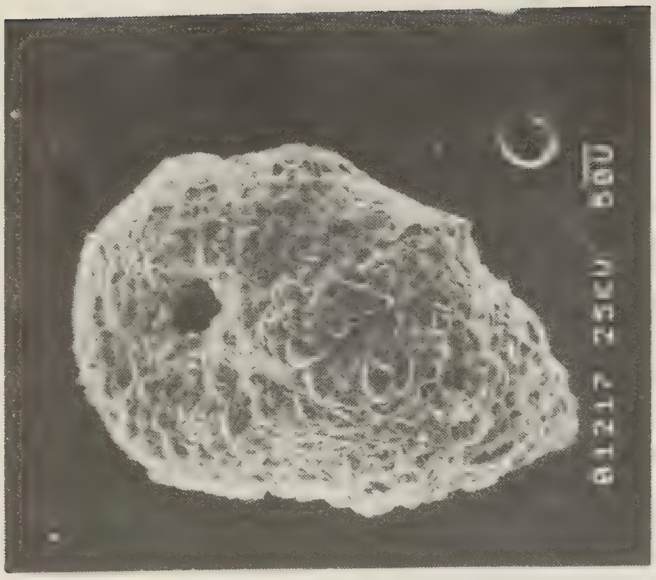
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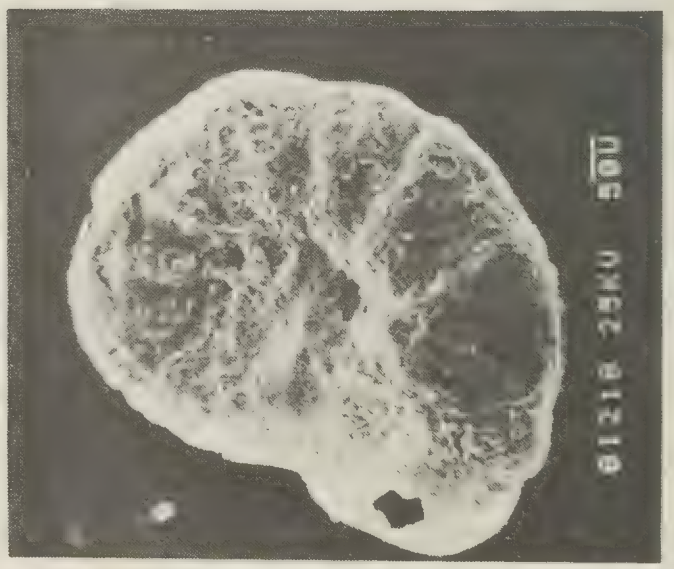
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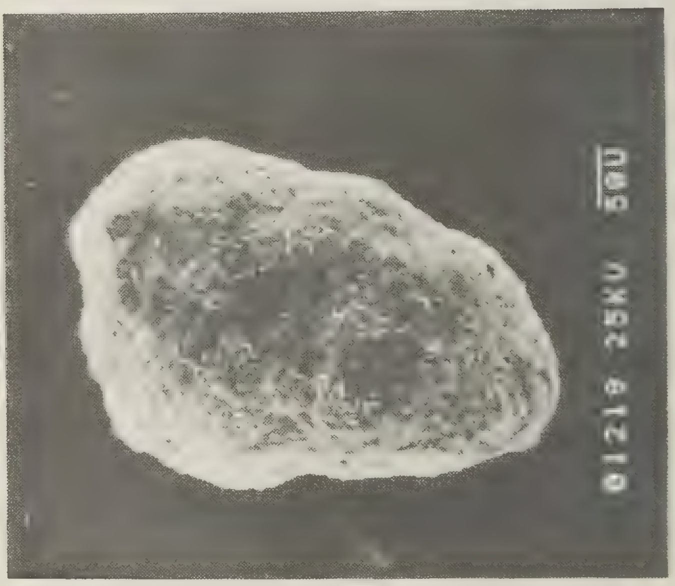
Gavelinella intermedia (Berthelin)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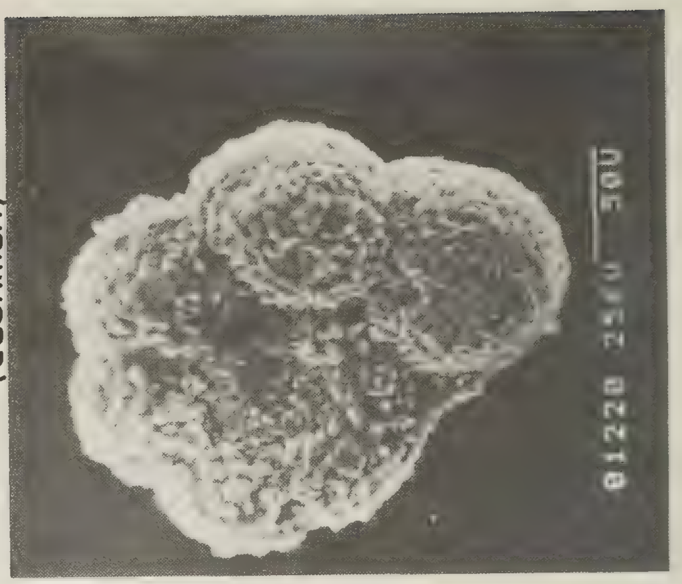
Arenobulimina advena (Cushman)


01220 25KU 30U

Hedbergella planispira (Tappan)

Plate 1 Hunstanton Red Rock Foraminifera

OBSERVATIONS ON THE STRATIGRAPHICAL RANGE AND MORPHOLOGY OF THE CRETACEOUS CRIBRIMORPH BRYOZOAN: UBAGHSIA CRASSA (LANG)

P.S. Whittlesea*

The bryozoan Ubaghsia crassa (Lang) has been known previously from only two specimens. Recently, eight more specimens have been found which require that the revised diagnosis (Larwood, 1962) be modified and the stratigraphical range of the species extended.

The species originally described by Lang (1922) as Batrachopora crassa and redescribed by Larwood (1962) as Ubaghsia crassa (Lang) was recorded by Lang as possibly from the boreal Maastrichtian of Rügen, East Germany, and from the Upper Senonian zone of Belemnitella mucronata of Catton, Norwich.

The new specimens all come from mucronata chalk sub-zones, the sequence of which in Norfolk is according to Peake and Hancock (1961); basal mucronata, Eaton Chalk, Weybourne Chalk, Beeston Chalk, and finally the Paramoudra Chalk. Five specimens come from the Eaton Chalk at the University of East Anglia; Cantley Pit, Cringleford; and Bluebell Road, Norwich. One comes from the low Weybourne Chalk at Eaton chalk pit, one comes from the junction of the Weybourne and Beeston Chalks at Catton, Norwich, and another from the high Beeston Chalk of St. James' Hollow, Heathgate, Norwich. The range of the species is therefore extended down from the Catton horizon to the low Eaton Chalk horizon at Cantley Pit, Cringleford.

Larwood based his redescription of the species on the only two specimens then available to him: Lang's holotype from Rügen, with just one complete very worn zooecium, and the Catton specimen, a small zoarium, though rather better preserved. He observed that the number of costae in the frontal wall of each zooecium were "unusually constant" for Bryozoa at seven. Most of the new material is of larger zoaria than either of the specimens that Larwood examined showing greater variation in this feature: from as few as four costae to as many as ten (see Table 1). A constant number of costae in the frontal wall should no longer be considered a diagnostic feature of this species.

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TABLE 1

Figures in the table show how many zooecia in each zoarium, (identified by catalogue numbers along the top of the table), have a given number of costae in the frontal wall. For details of specimens see "List of specimens examined" at the end of the paper.

Number of costae	U31	ET 17/1	C64	SJH 86/1
4	1	0	2	0
5	8	1	0	0
6	9	6	11	2
7	14	11	29	5
8	4	6	20	7
9	0	1	9	3
10	0	0	2	2

Larwood also suggested that a complete proximal oral shield might form by the fusion of the pair of proximal lateral oral avicularia above the orifice. Two of the specimens from the Eaton Chalk and one from the Weybourne Chalk show just one zooecium each with a complete proximal oral shield, although in each case the manner of its formation is slightly different. In one specimen, ET 17/1, the proximal lateral avicularia are united by an irregular band of secondary tissue. In another, U31, there is only one proximal-lateral avicularium and an irregular sheet of calcareous tissue arches over from where one would expect the other avicularium to be to fuse with the single avicularium. In the third, 15A, the avicularia lean over to meet and fuse at a midway point above the orifice.

Ubaghsia appears to be rather scarce: the twelve species Larwood described were represented by only 21 specimens, drawn from the many thousands of chalk

Bryozoa kept in the country's museums. Of the twelve species, four were described using only figures or photographs previously published, and three were represented only by their holotype specimens. The majority of the specimens come from the European Continent.

List of Specimens Examined:

Specimens from Norwich Castle Museum (N.C.M.)

(1) *Leeder* Collection. NCM accession number 113.972.

Dr. Leeder's catalogue numbers.

(B3) A small zoarium encrusting an echinoid test from a temporary section at Bluebell Road, Norwich.

(C64) A large zoarium encrusting a belemnite guard; *Belemnitella mucronata*, from Campling's Pit, Catton, Norwich.

(U31) A small zoarium encrusting a belemnite guard; *Belemnitella mucronata*, from a site in the grounds of the University of East Anglia.

(2) *R.M. Brydone* Collection. NCM accession number 76.937

Catalogue numbers allocated by various authors.

(76.937(30)) A small zoarium encrusting a piece of echinoid test from Catton, Norwich. (Figured Larwood 1962, pl.20 fig. 5).

(1);(7);(15A & B) Four zoaria encrusting three echinoid tests, from Cantley Pit, Cringleford, Norwich.

(3) Specimens from the author's collection

(SJH86/1) A small zoarium encrusting the base of a coral; *Coelosmilia granulata*, from two metres below the chalk/crag junction of St. James' Hollow, Heathgate, Norwich.

(ET17/1) A small zoarium encrusting a belemnite guard; *Belemnitella mucronata*, from the top 0.75m of Eaton chalk pit. Collected by Mr. M. Jackson.

Acknowledgements

I am especially grateful to Philip Cambridge, Peter Lawrance, and Norman Peake for the help that they all gave me in writing this paper. My thanks also to Mike Jackson for donating specimen ET17/1, and to Jane Bexon for help in producing the plates.

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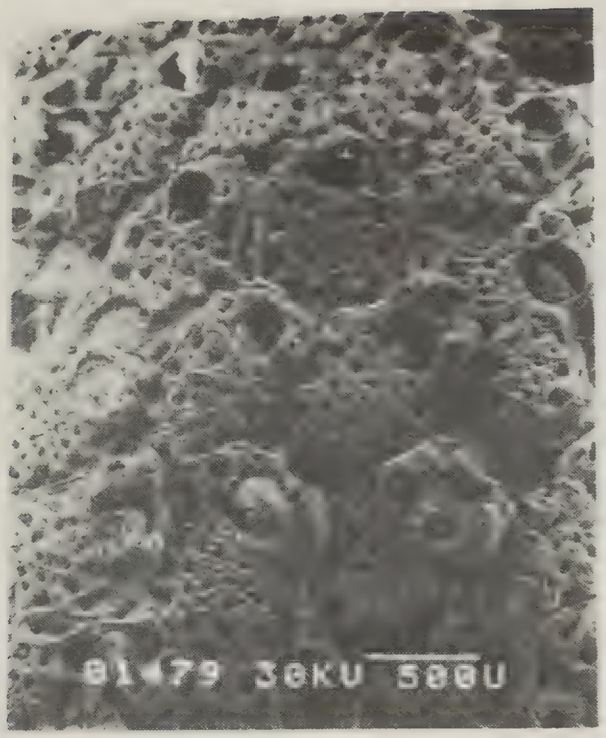
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Fig. 1 Adult zoecia showing worn oral shields (C64)

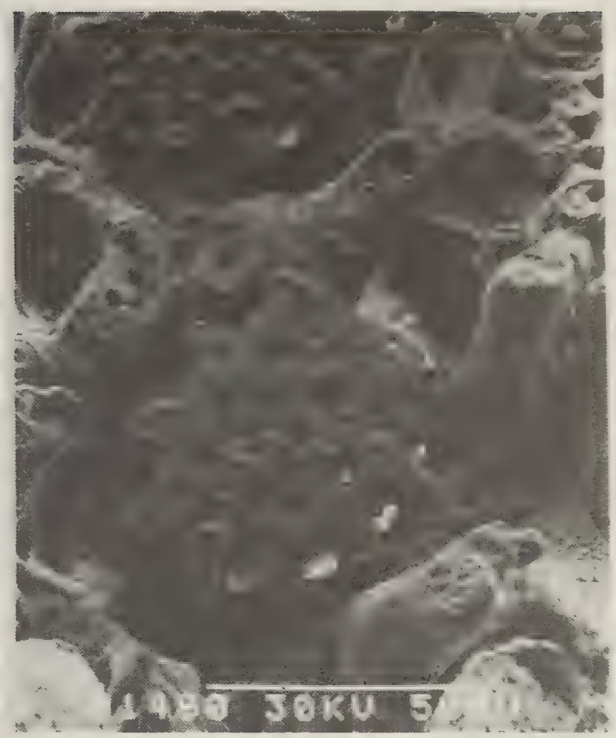

Fig. 2 Detail of Fig. 1. Adult zoecium showing worn oral shield (C64)

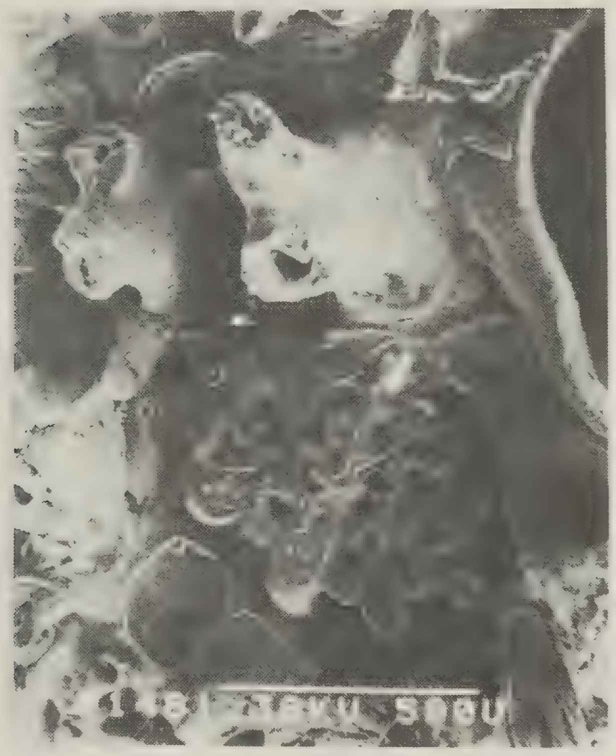

Fig. 3 Adult zooecium with robust oral shield (SJH 86/1)

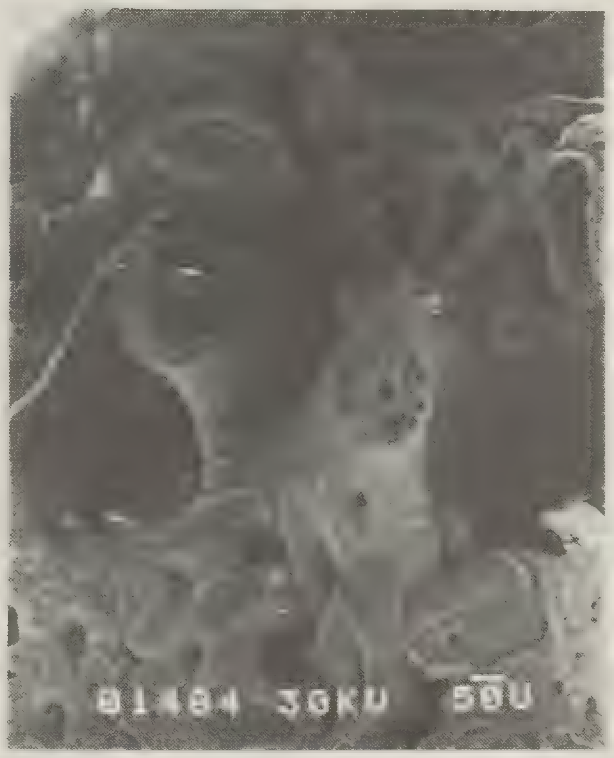
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Fig. 4 Detail of two zooecia showing broken oral shield and distal oral spines (SJH 86/1)

Plate 1 Ubaghsia crassa (Lang)

The scale bar in Figs. 1-3 represents 0.5 mm, and in Fig. 4 it represents 0.05 mm

Bull. geol. Soc. Norfolk, 33, 32-33

THE OCCURRENCE OF THE BRACHIOPOD GENUS RUGIA STEINICH IN THE NORWICH CHALK

P.S. WHITTLESEA*

The brachiopod genus *Rugia* was described by Steinich (1963b) from the Maastrichtian (Upper Cretaceous) of the Isle of Rügen, East Germany. Subsequently, Surlyk (1970) described two further species from the Danish Maastrichtian: *Rugia tegulata* and *Rugia spinosa*.

In the course of my investigation of the fauna of the Norwich Chalk by disaggregation and washing of samples, a single specimen of *Rugia spinosa* was found. The specimen was recovered from a chalk sample collected approximately two metres from the top of Eaton chalk pit, Norwich, in the lowest four to five metres of the sub-division of the zone of *Belemnitella mucronata* known as the Weybourne Chalk. A fuller discussion of the sub-divisions of the *mucronata* Chalk may be found in Peake and Hancock (1961). The specimen is rather larger than those described from Denmark: 2.00 mm long, compared with 1.20 mm.

Surlyk (1970b) succeeded in dividing the Danish Maastrichtian into ten zones based on the brachiopods, and he nominated *Rugia spinosa* as the zone-fossil for his second zone from the bottom. The specimen from Eaton is from the Upper Campanian, a lower horizon than the Danish one, and probably the lowest yet recorded for *Rugia* in Europe.

Surlyk (1972) demonstrated that *Rugia* was adapted to living on very small hard substrates such as bryozoa. This specimen was collected from a hard-ground characterised by an abundance of erect cyclostome and cheilostome bryozoa, and numbers of small and juvenile brachiopods.

Material examined: author's collection

Specimen no. ET26/1, from two metres below the chalk/crag junction in Eaton chalk pit, Norwich, Zone of *Belemnitella mucronata*; sub-division: Weybourne Chalk.

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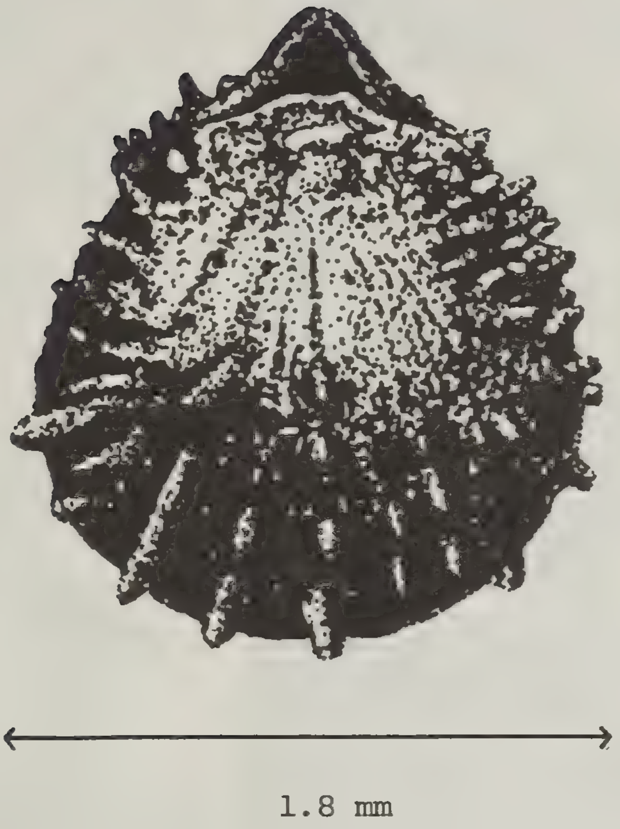

Fig. 1 Rugia spinosa: dorsal view, from Eaton Chalk pit

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"Collecting at the Bulcamp excavations, 21 July 1979"

Bull. geol. Soc. Norfolk, 33, 35-44

THE CRAG OF BULCAMP, SUFFOLK

B.M. Funnell*

Summary

Foraminiferal and mollusc assemblages from shell beds of the Norwich Crag Formation of Bulcamp indicate shallow-water (inner sublittoral to intertidal) accumulation under temperate (interglacial) conditions, probably near the mouth of an estuary.

The age of the deposits is either Antian or Bramertonian.

Introduction

In 1871, in his classic paper on the "Crag-beds of Suffolk and Norfolk", Prestwich described a highly fossiliferous pit on the north side of the Blyth Valley. It was already obscured by the time that Reid wrote his monograph on the Pliocene deposits of Great Britain in 1890 (see p.105), but in 1979 the Geological Society of Norfolk, assisted by the Geological Group of Ipswich, decided to re-excavate the pit as part of its summer field programme (Cambridge, 1982).

Prestwich (1871, pp.344-5) described the pit as "near Bulcamp Union", i.e. near the Union Workhouse (the buildings of which now house the Blythburgh and District Hospital), and "very little above the level of the river".

There are three disused pits marked south of Union Farm on the current (1972) revised edition of the 1:10,000 Ordnance Survey map. One is very close to the farmhouse itself, and well above the level of the river. The other two are due south and south-south-west of the farm buildings just above the river flood-plain. It was decided to excavate the larger of these two (Prestwich's account referred to a section 20 feet (6.1m) deep), which is the pit south-south-west of the farm buildings, at TM 4420 7545.

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Prestwich's account

Prestwich's description of the pit is succinct and the salient features can be quoted in full. His Fig. 25 is reproduced, without the engraved shading, as Fig. 1 of this paper.

"Some years since, a section nearly 20 feet deep was well exposed (Fig. 25); now little is to be seen.

In appearance and colour the pit is precisely like a Red-Crag pit, and it will be observed that we have here a repetition of the marks of erosion which we have noticed between the two divisions of the Red Crag of the Sutton district; or it may only be an eroded shoal in the lower division, as at Ramsholt (Fig. 6). The shells I have found there are as under:-

Lists of fossils from Bulcamp-pits of the Union. (See also the general list).

Abra alba
Actaeon Noae
Astarte
Cardium edule
Corbula nucleus
Cyprina islandica
Leda myalis
Mactra ovalis
Mactra subtruncata
Mya arenaria
Mya truncata
Mytilus edulis
? Panopaea norvegica
Tellina lata
Tellina obliqua
Tellina praetenuis

Scrobicularia piperata

Buccinum undatum
Cerithium tricinctum
Conovulus pyramidalis
Bulimus
Littorina littorea
Natica catena
Paludina lenta
Purpura lapillus
Trophon antiquum
Turritella communis
Scalaria groenlandica

Balanus crenatus
Claw of crab
Vertebrae of fish "

Reid (1890, pp.105-6) comments:

"The list of fossils, however, shows no trace of any horizon below the Norwich Crag, the 46 species mentioned by Prof. Prestwich being all Norwich Crag forms, and including many land and freshwater mollusca rare or unknown in the older deposits".

The 1979 section

The 1979 section was excavated in what appeared to be the overgrown and degraded north wall of the old pit. It consisted of two parts. Firstly a trench, to the west, extending from approximately +5.1m O.D. at the surface (samples 1 to 5, Ī and 2.̄8 were taken at the positions marked on Fig. 2) to a depth of approximately 5.8m (-0.7m O.D.). Secondly a face, to the east, extending east-west and north-south. from the surface at approximately +3.9m O.D. to a maximum depth of 2.9m (1.0m O.D.). Samples A, B and C were taken at the positions marked on Fig.2.

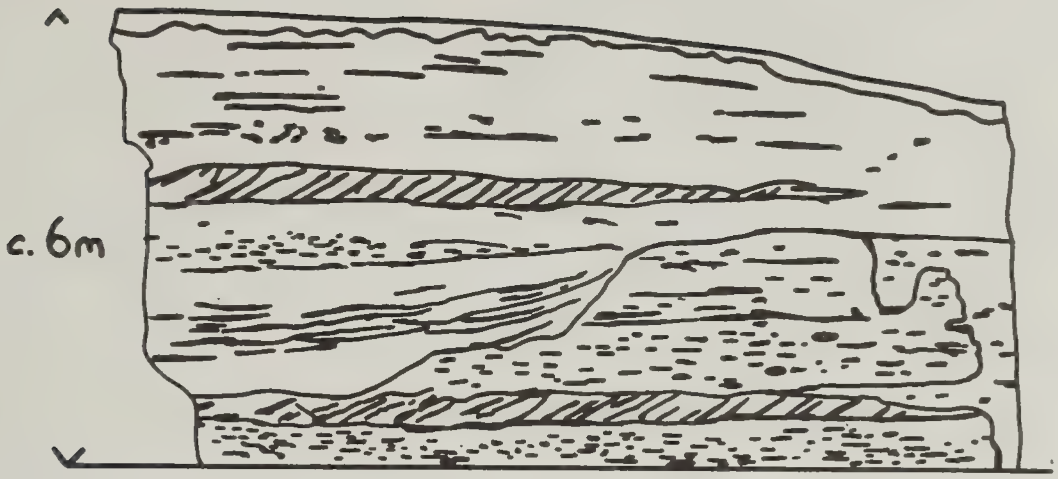


Fig. 1 Pit near Bulcamp Union (after Prestwich 1871, p.344, Fig. 25)

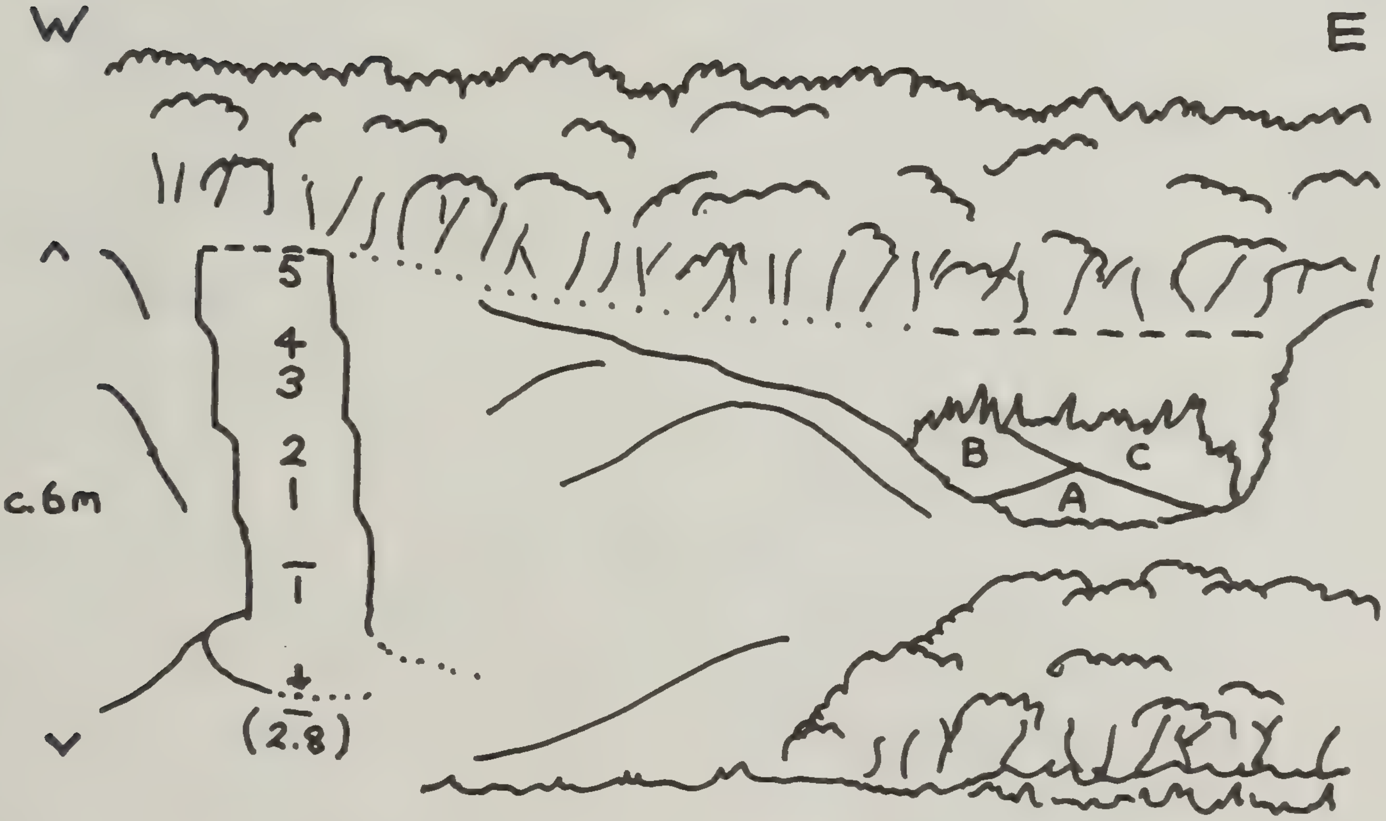

W
E
5
4
3
2
1
1
+
(2.8)
c.6m
B
C
A

Fig. 2 Sketch of excavations 1979, showing position of principal samples referred to in text

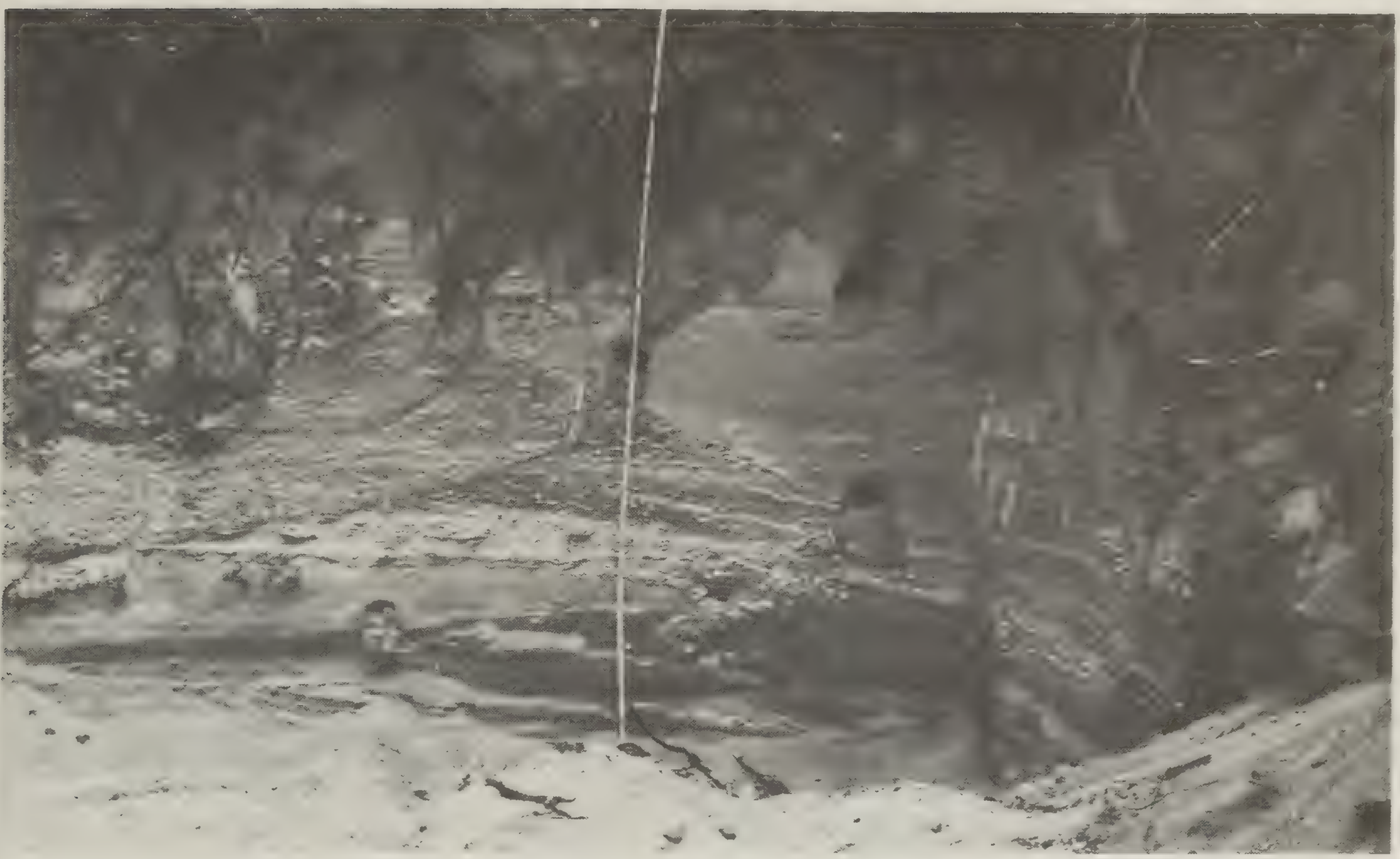
Sedimentology

Very little lateral variation could be seen in the western trench. Very shelly sand commenced about 0.5m below the ground surface, where sample 5 was taken, and continued without much vertical variation except for slight changes in shell and fine sand/silt content to a depth of 3.0m below surface, at which level sample 1 was taken. The >2 mm, mainly shell content varied between 12 and 20%. The sand comprised 73 and 80% and was unimodal, 21 to 35% falling in the 180-250 μm fraction. The trench was excavated 2.8m below sample 1, in damp, essentially unfossiliferous sands. (A very few foraminifers were recovered from these lower samples.) The lower sands contained no material larger than 2 mm, and comprised 99% sand, which was still unimodal, with 52 to 53% falling in the 180-250 μm fraction.

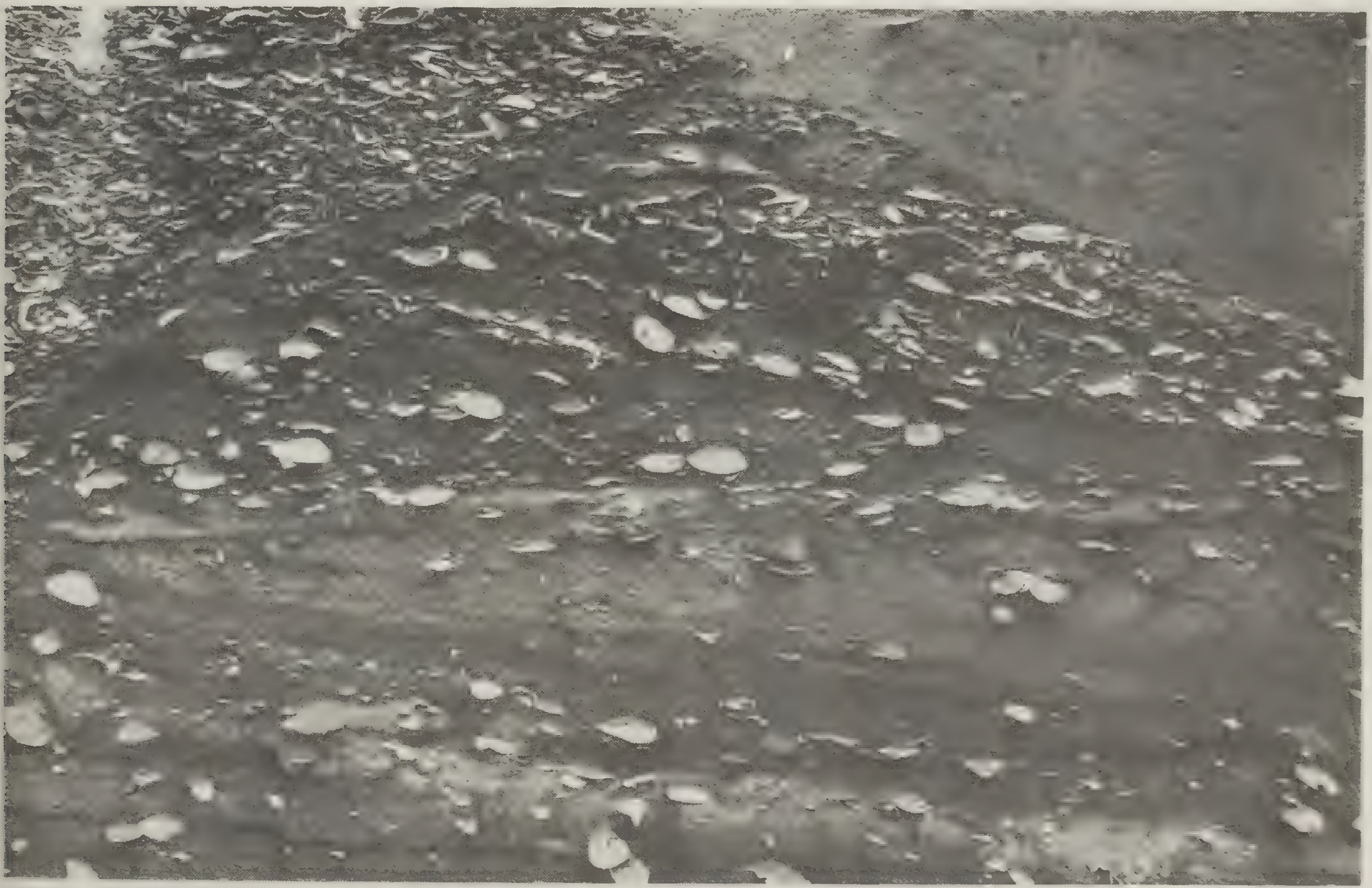
The eastern face was much more interesting, showing three distinct shelly beds, with erosional contacts, illustrated in Plate 1. The erosional contacts meet at a point c. +2.2m O.D. The lowest bed, from which sample A was obtained, contains relatively little (2%) material >2 mm, and is 97% sand, which is unimodal with 56% falling in the 250 to 355 μm fraction. Sample B, from the second bed, contains most (11%) material >2 mm, and is 89% sand, which is unimodal with 25% falling in the 180 to 250 μm fraction. Finally, sample C, from the uppermost bed, contains an intermediate amount (8%) of material >2 mm, and the 91% of sand is again unimodal with 25% in the 250 to 355 μm fraction. None of the beds in the eastern face is quite as shelly as those in the western trench, and the sand is also slightly coarser on average. It is possible that the wedge of shelly sand comprising the middle bed (sample B) opens out westwards and passes laterally into the shelly sands of the trench. Certainly the mechanical composition of this middle bed has the greatest similarity to the shelly sands of the trench.

Foraminifera

Foraminiferal assemblages were prepared both as carbon tetrachloride floats and by picking the residual 500-250 μm fraction. The results are given in Table 1.



(a) General view of north face of eastern excavations showing erosional contacts between shell beds A, B and C



(b) Close-up of shell bed A and its junction with overlying shell beds B and C

Plate 1

Table 1: Percentage Composition of Bulcamp Foraminiferal Assemblages

Sample Number	5	4	3	2	1	$\bar{1}$	$\bar{2}.8$	C	B	A
Depth m O.D.	+4.6	+3.6	+3.1	+2.4	+2.1	+1.1	-0.7	>+2.2	+2.2	<+2.2
Total no. Specimens	359(220)	433(295)	446(313)	221(145)	214(96)	23(21)	3(1)	561(397)	264(156)	964(49)
Elphidiella hannai	56 (73)	51 (60)	58 (66)	51 (59)	53(64)	43(43)	100(100)	46 (57)	52 (67)	48(43)
Ammonia beccarii	26 (9)	31 (19)	25 (15)	36 (26)	39(18)	35(33)	-(-)	27 (13)	31 (14)	44(51)
Elphidium pseudolessonii	5 (6)	5 (6)	3 (3)	5 (6)	3 (6)	17(19)	-(-)	6 (8)	6 (8)	2 (4)
Elphidium frigidum	1 (1)	2 (2)	1 (1)	4 (3)	1 (2)	4 (5)	-(-)	5 (7)	- (-)	0 (-)
Elphidium excavatum	5 (6)	6 (8)	5 (6)	- (-)	2 (5)	- (-)	-(-)	8 (8)	5 (6)	3 (-)
Cibicides lobatulus	4 (3)	4 (5)	4 (5)	2 (2)	2 (5)	- (-)	-(-)	3 (4)	2 (3)	1 (2)
Elphidium haagensis				0 (-)					1 (-)	0 (-)
Elphidium macellum								0 (-)		
Elphidium margaritaceum		0 (-)	0 (-)	1 (1)				1 (2)	0 (1)	0 (-)
Elphidium orbiculare	1 (-)									
Elphidium williamsoni	0 (-)		2 (3)	0 (1)				0 (-)		0 (-)
Elphidium sp.			0 (-)	1 (1)						
Bucella frigida								0 (0)	1 (-)	
Cibicides subjaidingeri									1 (-)	
Eponides repandus		0 (-)							1 (-)	
Guttulina								0 (0)		
Lenticulina	1 (1)		0 (0)						0 (1)	
Planorbulina mediterranensis								0 (0)		
'Rosalina parisiensis'	0 (-)		0 (-)							
Textularia suttonensis			0 (0)							
reworked Cretaceous spp.								1 (0)		

The plain figures in the table represent "total", i.e. "floated" specimens, plus those obtained by picking the "sink" residue of the carbon tetrachloride flotation. The numbers in brackets represent the carbon tetrachloride "float" yield only. It will be seen from this that the 'float' yield varied between 91 and 5% of the total ("float" + "sink") population! Ammonia beccarii in particular tends not to "float".

Mollusca

In order to get an idea of how à selective collection of mollusc shells from the exposed face would compare with those obtained from bulk sediment samples, shells were taken from the exposed face in the vicinity of samples 1 to 5. The results are given in Table 2.

It is easily seen that the commonest bivalves are:-
Macoma praetenuis (30-56%), Spisula sp. (19-32%), Cerastoderma edule (8-35%), Macoma obliqua (up to 15%), Macoma calcarea (up to 8%) and Mytilus edulis (up to 3%). C. edule may be less common at the top of the section. M.obliqua, M. calcarea and M. edulis appear to be less common at the bottom of the section.

The commonest gastropods are:
Littorina littorea (35 to 57%), Cerithium tricinctum (21 to 53%) and Natica catena (6 to 21%). L. littorea may decrease in abundance relative to C. tricinctum towards the top of the section.

Taken together the decrease in L. littorea and C. edule towards the top of the section could indicate that intertidal molluscs are slightly less important in the assemblages at the top of the sequence. The bivalve:gastropod ratio seems to increase up the section.

The average rib count of 23.1 on Cerastoderma edule would seem to imply a salinity of 26 ± 2^{o}/oo if found on the modern Dutch coastline (Eisma, 1965); it is not distinguishable from values found for Cerastoderma edule in the modern chenier ridges of Bradwell-on-Sea, Essex at the mouth of the Blackwater estuary.

Table 2: Relative proportions (in percentages) of bivalve and gastropod molluscs taken from exposed face.

Sample Number	5	4	3	2	1
No. of bivalve valves	75	108	72	90	23
Macoma praetenuis	49	37	37	56	30
Spisula sp.	32	23	19	20	30
Cerastoderma edule	8	19	24	19	35
Macoma obliqua	4	7	15	6	-
Macoma calcarea	4	8	1	-	-
Mytilis edulis	3	2	1	-	-
'Cyprina'	-	1	-	-	-
Nucula sp.	-	3	-	-	-
Yoldia sp.	-	-	1	-	-
Arctica islandica	-	-	-	-	1
No. of gastropod shells	17	57	42	58	31
Littorina littorea	35	39	43	57	55
Cerithium tricinctum	53	44	26	21	29
Natica catena	6	9	21	19	6
Nucella lapillus	-	2	2	-	6
Viviparus sp.	6	-	-	-	-
Peringia ulvae	-	5	-	-	-
Buccinum undatum	-	2	-	-	-
Scalaria groenlandica	-	-	2	-	-
Ringicula sp.	-	-	2	-	-
Amauropsis islandica	-	-	-	2	-
Ellobium pyramidale	-	-	-	2	-
Bivalve:gastropod ratio (2 valves = 1 bivalve)	2:1	1:1	5:6	4:5	1:3
C. edule rib count (av. 23.1)	23.5	22.4	23.4	23.7	23.1

Provisional Conclusions

1. As Reid (1890, p.105) concluded, this is clearly a Norwich Crag, or as we would now say Norwich Crag Formation deposit. Both the foraminifers and the molluscs confirm this.

2. The foraminifers have a shallow-water (inner sub-littoral to intertidal) aspect and indicate temperate (i.e. interglacial) climatic conditions. The interglacial and intertidal species *Ammonia beccarii* is particularly well represented. On the other hand it is not yet clear whether this assemblage is Antian, corresponding to the lowest shell beds on the coast at Easton Bavents (Funnell and West, 1962), or Bramertonian, corresponding to the lower shelly deposits at Bramerton, near Norwich (Funnell, Norton and West, 1979). Like some of the lowest deposits at Bramerton the Bulcamp shell beds include a few relict, probably reworked species such as *Cibicides subhaidingeri* and *Eponides repandus*, which are found commonly in the Red Crag Formation. So far however, there is no reason to exclude an Antian age based on the foraminifers. It is possible that a basis for distinguishing between foraminiferal assemblages of these two stages will arise from current investigations of boreholes in central and eastern Suffolk.

3. The molluscs recorded here have an equally shallow-water (inner sublittoral to inter-tidal) aspect and include abundant specimens of *Cerastoderma edule*, *Littorina littorea* and *Cerithium tricinctum*. They too comprise a Norwich Crag Formation assemblage, but it is again not possible to distinguish between an Antian or Bramertonian age. Amino acid analysis of *Mya* shell fragments from the Bulcamp section proved inconclusive as far as precise age determination was concerned (Davies *et al*. 1982).

Acknowledgements

I am most grateful to Anne Funnell for undertaking the tedious task of extracting the foraminifers from the "sink" residue after carbon tetrachloride flotation. I am also grateful to Philip Cambridge for identification of some of the less common species of mollusc in my samples.

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Draft received September 1981; revised May 1983.

Corrigendum

In Davies, A.M.C., Funnell, A.M. & Funnell, B.M. (1982) Bull. geol Soc. Norfolk, 32, on page 40, please substitute enantiomers wherever stereoisomers is printed, and diastereomers wherever enantiomers is printed.

Bull. geol. Soc. Norfolk, 33, 45-53

DEBENHAM AND STRADBROKE, TWO CRAG BOREHOLES IN SUFFOLK COMPARED

B.M. Funnell* and S.K. Booth†

Abstract

Examination of the foraminifers from a shelly Crag borehole sunk to -30m O.D. at Debenham suggests, by comparison with the sequence from Stradbroke, that the main part of the sequence is Ludhamian in age, with the possibility that the lowest part is Pre-Ludhamian, and that a clayey sequence overlying the shelly beds may be upper or post-Ludhamian.

Introduction

One of the more remarkable aspects of the early Pleistocene of Suffolk is the large SW- trending Stradbroke trough in which marine Crag deposits occur to depths of as much as -45m O.D. at distances of more than 20 km inland from the present coastline. The possible origin of this trough has been discussed by several authors including Woodland (1964) and Funnell (1972). Boreholes penetrating the central (Stradbroke) and northern marginal (Hoxne) deposits in this trough have been described by Lord (1969) and Beck et al. (1972). Recently, samples have become available from an exploratory water resources borehole, drilled just north of Debenham on the southern margin of the trough by the Norfolk and Suffolk River Division of the Anglian Water Authority, primarily to investigate the hydrogeological potential of the Crag for a proposed river regulation borehole serving the River Deben. It is the purpose of this paper to make a brief description and comparison of the sedimentary sequences and foraminiferal (microfossil) content of the Debenham and Stradbroke boreholes.

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Debenham

The Debenham borehole was sunk at TM 1763 6425 on the west side of the road just north of Debenham. Ground level was approximately +37m O.D. Samples were taken at 2m intervals. The sequence was as follows (figures in brackets are depths relative to O.D.):

0 to 2m (+37 to +35m)	Grey-green/blue silty clay
2 to 3m (+35 to +34m)	Yellow-brown sand
3 to 7.5m (+35 to +29.5m)	Soft, yellow-brown silty sand
7.5 to 9m (+29.5 to +28m)	Soft, yellow-brown sand, with trace of gravel at base
9 to 13m (+28 to +24m)	Orange-yellow, coarse sand
13 to 16.5m (+24 to +20.5m)	Soft, yellow, fine sand
16.5 to 19.5m (+20.5 to +17.5m)	Soft, yellow, fine sand, with coarser sand and gravel
19.5 to 20.5m (+17.5 to +16.5m)	Grey-blue, fine sand, with some gravel
20.5 to 26.5m (+16.5 to +10.5m)	Blue-green sticky clay, with some thin lenses of silty clay
26.5 to 30m (+10.5 to +7m)	Silty sand with some clay lenses
30 to 33m (+7 to +4m)	Coarse sand with traces of shell fragments
33 to 38m (+4m to -1m)	Fine sand with shells
38 to 50m (-1 to -18m)	Green-blue, fairly coarse sands with much fragmental shell
55 to 57m (-18 to -20m)	Green-blue sand with hard nodules and thin laminae of cemented sand
57 to 61m (-20 to -24m)	Hard, cemented shell/sand
61 to 67m (-24 to -30m)	Blue, coarse shelly sand
67 to 69m (-30 to -32m)	Chalk

Microfossils (foraminifers, plus some ostracods) have been recovered from samples at 22 to 66m inclusive. Samples of clayey sediment from 22 to 30m have been sent for examination for pollen to Professor R.G. West of Cambridge University.

Stradbroke

Two boreholes have been sunk at Stradbroke, the first in 1933, the second, financed by an NERC Research Grant, in 1969. Both were situated in the grounds of Stradbroke Priory, approximately 6m apart, at TM 2326 7382. Ground level was +54.83m. The 1969 borehole was extensively sampled. The sequence was as follows:

0 to 1m (+54.8 to +53.8m)	Made ground
1 to 20.7m (+53.8 to +34.1m)	Hard, dark blue/grey clay with chalk pebbles
20.7 to 24.7m (+34.1 to +30.1m)	Red coarse sands and gravels with chalk and flint pebbles in the upper part
24.7 to 31.2m (+30.1 to +23.6m)	Grey fine sand
31.2 to 33.5m (+23.6 to +21.3m)	Dark blue/grey silty clay
33.5 to 66.3m (+21.3 to -11.5m)	Green/grey sands with thin clay bands, becoming coarser and more shelly with depth. Hard, cemented nodules and bands of sand and clay also occur.
66.3 to 67.7m (-11.5 to -12.9m)	Blue/grey clay
67.7 to 70.9m (-12.9 to -16.1m)	Green/grey silty sand with shells
70.9 to 80.8m (-16.1 to -26.0m)	Blue/grey clay
80.8 to 94.2m (-26.0 to -39.4m)	Grey, silty shelly sands with occasional thin clay banks and claystone nodules
94.2 to 96.0m (-39.4 to -41.2m)	Chalk

Microfossils (foraminifers, plus some ostracods) have been recovered from samples between 45.1 and 94.2m inclusive. Pollen analysis of the clays in the sequence by Beck (1971) indicated the Ludhamian stage from 24.7 to c. 69.8m, and Pre-Ludhamian deposits from c. 69.8 to 94.2m.

Foraminifera

Foraminifera were obtained by carbon tetrachloride flotation and only the 500-250 μm size fraction was examined. The quantitative results are therefore not directly comparable with previous publications on Crag foraminifera. (Many thicker shelled or mineral-infilled Crag foraminifers sink in carbon tetrachloride - see Funnell pp.35-44 this volume).

Discussion

Examination of Tables 1 and 2 shows that the 'floated' foraminiferal assemblages are not particularly abundant either in the Debenham sequence anywhere down to 66m (-29m O.D.) or in the Stradbroke sequence above 69m (-14.2m O.D.).

In the lower part of the Stradbroke borehole they are much more abundant and many more species are represented. This part of the Stradbroke sequence corresponds almost precisely with the Pre-Ludhamian pollen stage of Beck *et al.* (1972) who drew the boundary with the Ludhamian at c. -15m O.D. Only some of the trends in the foraminifers of the Pre-Ludhamian noted by Beck *et al.*, on the basis of unfloated assemblages, are apparent in the "floated" assemblages. *Pararotalia serrata* in particular is essentially unrepresented in the floated assemblages and *Elphidium frigidum* does not appear in the floated assemblages of the upper part of the Pre-Ludhamian as it does in the unfloated assemblages. Nevertheless several features such as the occurrence of *Globigerina bulloides*, *Nonionella janiformis/turgida* and *Textularia suttonensis* towards the top of the Pre-Ludhamian are apparent in both floated and unfloated assemblages and *Elphidium haagensis* occurs sparingly throughout.

At first sight no part of the Pre-Ludhamian seems to be present at Debenham as least as far as the foraminifers are concerned, even though the deposit descends to -29m O.D. whereas the top of the Pre-Ludhamian at Stradbroke seems to extend as high as -14.2m O.D. Some species that seem to be restricted to the Pre-Ludhamian floated assemblages at Stradbroke do however occur sporadically in the Debenham section. These are: *Ammonia beccarii*, *Cassidulina laevigata*, *Globigerina bulloides* and *Textularia suttonensis*, together with some specifically unidentified miliolids and polymorphinids. In addition *Pararotalia serrata* has been observed in the residues of the floats from 66m (-29m O.D.) up to 46m (-9m O.D.) together with thick-shelled *Ammonia beccarii*, actually occurring up to 34m (+3m O.D.) along with textulariids, bryozoans and regular echinoid spines that are more characteristic of Red Crag Formation than Norwich Crag Formation residues. Therefore although the general presumption must be that the shelly Debenham section is entirely Ludhamian by comparison with Stradbroke, it is not inconceivable that the lowermost samples from 52m (-15m O.D.) downwards may be older, the similarity with Stradbroke being obscured by the overall paucity of foraminifers in the Debenham section at that level.

It remains to be seen whether the clayey parts of the Debenham section between 22 and 30m (+15 to +7m O.D.) will yield Ludhamian pollen as they did at the equivalent level at Stradbroke or whether a later stage such as the Thurnian is represented.

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Table 1 Debenham

Foraminifera 500 to 250 µm, CCl_4 float

Depth m O.D.	(+15)	(+13)	(+11)	(+9)	(+7)	(+5)	(+3)	(+1)	(-1)	(-3)	(-5)	(-7)
Depth m (b.s.)	22	24	26	28	30	32	34	36	38	40	42	44
Total no. specimens	1	1	1	5	6	5	22	13	27	21	30	63
Elphidiella hannai	100	100	-	100	80	80	77	85	70	62	53	60
Cibicides lobatulus	-	-	-	-	-	20	9	8	-	14	17	30
Elphidium excavatum	-	-	-	-	-	-	9	-	11	19	23	3
Elphidium frigidum	-	-	-	-	-	-	-	-	-	-	-	-
Ammonia beccarii	-	-	-	-	20	-	-	-	-	-	-	-
Bulimina aculeata	-	-	-	-	-	-	-	-	4	-	-	2
Cassidulina laevigata	-	-	-	-	-	-	-	-	-	5	-	-
Elphidium williamsoni	-	-	-	-	-	-	5	-	7	-	7	2
Elphidium spp.	-	-	-	-	-	-	-	8	-	-	-	3
Globigerina bulloides	-	-	-	-	-	-	-	-	-	-	-	-
miliolid	-	-	-	-	-	-	-	-	-	-	-	-
Oolina sp.	-	-	100	-	-	-	-	-	4	-	-	-
polymorphinid	-	-	-	-	-	-	-	-	-	-	-	-
Quinqueloculina sp.	-	-	-	-	-	-	-	-	-	-	-	-
Textularia suttonensis	-	-	-	-	-	-	-	-	-	-	-	-

Table 1 Debenham (continued)

Foraminifera 500 to 250 µm, CCl_4 float

Depth m O.D.	(-9)	(-11)	(-13)	(-15)	(-17)	(-19)	(-21)	(-23)	(-25)	(-27)	(-29)
Depth m (b.s.)	46	48	50	52	54	56	58	60	62	64	66
Total no. specimens	62	82	18	24	26	24	2	6	0	3	3
Elphidiella hannai	65	68	78	67	50	83	100	100	-	67	67
Cibicides lobatulus	18	15	11	21	35	8	-	-	-	33	33
Elphidium excavatum	6	6	11	8	-	-	-	-	-	-	-
Elphidium frigidum	-	4	-	-	4	-	-	-	-	-	-
Ammonia beccarii	-	-	-	-	-	-	-	-	-	-	-
Buliminia aculeata	-	-	-	-	-	-	-	-	-	-	-
Cassidulina laevigata	-	-	-	-	-	-	-	-	-	-	-
Elphidium williamsoni	5	1	-	-	-	4	-	-	-	-	-
Elphidium spp.	2	1	-	-	4	-	-	-	-	-	-
Globigerina bulloides	-	-	-	-	4	-	-	-	-	-	-
miliolid	2	1	-	-	-	-	-	-	-	-	-
Oolina sp.	-	-	-	-	-	-	-	-	-	-	-
polymorphinid	2	1	-	-	-	4	-	-	-	-	-
Quinqueloculina sp.	2	2	-	-	-	-	-	-	-	-	-
Textularia suttonensis	-	-	-	4	4	-	-	-	-	-	-

Table 2 Stradbroke

Foraminifera 500 to 250 µm, CCl_4 float

Depth m O.D.	(+9.7)	(+4.4)	(-0.2)	(-5.8)	(-8.0)	(-8.4)	(-10.7)	(-14.2)	(-15.8)	(-16.7)	(-29.5)	(-30.4)	(-31.3)	(-39.4)
Depth m (b.s.)	45.1 /	50.4 /	55.0 /	60.6 /	62.8 /	63.2 /	65.5 /	69.0 /	70.6 /	71.5 /	84.3 /	85.2 /	86.1 /	94.2
Total no. Specimens	10	72	33	44	12	14	13	390	179	114	455	410	122	51
Elphidiella hannai	90	49	55	59	42	50	31	18	26	4	54	62	53	41
Cibicides lobatulus	10	25	21	20	25	7	23	65	54	40	16	17	12	18
Elphidium excavatum	-	12	9	7	17	21	8	2	3	18	6	5	11	6
Elphidium frigidum	-	6	3	-	17	7	8							
Elphidium incertum	-	1	-	-	-	-	8							
Buccella frigida	-	-	-	-	-	7	-	1	-	-	2	2	4	6
Bulimina aculeata	-	1	-	-	-	-	-	-	1	-	-	0	1	-
Dorothia gibbosa	-	-	-	5	-	-	-	0	-	-	-	-	-	-
Elphidium pseudolessonii	-	3	-	2	-	-	-	0	1	-	-	-	-	-
Elphidium williamsoni	-	1	3	-	-	7	8	-	-	2	-	-	-	-
Globigerina bulloides	-	1	-	-	-	-	-	0	2	4	1	-	-	-
Quinqueloculina seminulum	-	-	9	7	-	-	15	2	1	-	1	-	-	14
Ammonia beccarii								2	2	1	0	0	-	-
Cassidulina laevigata								2	2	-	1	1	-	-
Cibicides pseudoungeriana								-	-	1	-	-	-	-
Cibicides subhaidingeri								0	-	-	0	0	-	-
Elphidium haagensis								-	-	-	-	-	-	-
Elphidium margaritaceum								-	-	25	2	1	1	-
Eponides repandus								-	-	1	-	0	-	-
Faujasina subrotunda								-	-	-	-	-	-	2
Globulina gibba								2	-	1	1	1	2	2
Globulina aff. myristiformis								1	1	-	0	2	1	-

Guttulina lactea	0	-	-	0	-	-	-
Lagena sp.	-	1	1	1	-	-	-
Lenticulina sp.	1	1	-	0	0	1	4
Nonion sp.	-	-	-	0	0	-	-
Nonionella janiformis	0	1	-	0	-	-	-
Oolina sp.	-	-	-	0	-	-	2
Pararotalia serrata	0	-	-	0	-	-	-
Planorbulina mediterranensis	0	1	-	-	-	-	-
Polymorphina sp.	-	-	-	-	0	-	-
Pullenia quinqueloba	1	1	1	-	0	-	2
Pullenia sphaeroides	3	2	-	-	-	1	-
Pyrgo sp.	0	-	-	0	-	-	-
Rosalina sp.	1	-	-	-	0	-	2
Textularia gramen	0	-	-	0	1	-	-
Textularia sagittula	-	-	-	0	-	-	-
Textularia suttonensis	1	2	3	1	0	1	-

Bull. geol. Soc. Norfolk, 33, 54-62

PRELIMINARY NOTE ON THE FORAMINIFERA AND STRATIGRAPHY OF C.E.G.B. SIZEWELL BOREHOLES L & S

B.M. Funnell[*]

Summary

Foraminifers from site investigation boreholes at Sizewell suggest the possible presence of Bramertonian, Baventian, ?Antian, ?Thurnian and Pre-Ludhamian deposits, but this is not confirmed/established on the basis of pollen analysis.

Introduction

31 sediment samples were taken, in company with Professor R.G. West and Dr. D.J. Horne, on 27 November 1980. Depths below surface are given in Tables 1 and 2.

All samples were washed, sieved, and the dry 500-250 µm fraction "floated" in carbon tetrachloride to obtain a concentrate of foraminifers. Not all the contained foraminifers are recovered by this method. Specimens larger than 500 µm, and smaller than 250 µm are not recovered; neither are those that 'sink' in carbon tetrachloride, which may be 5 to 95% of the total number of foraminifers in the size fraction (Funnell, pp.35-44, this volume). Assemblages prepared by the same method are available for comparison from boreholes at Debenham and Stradbroke, c.30 km inland from Sizewell (Funnell and Booth, pp.45-53, this volume). Concentrates were prepared and picked by Paul Orford, and identified by the author.

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Borehole succession

(1) In borehole L the sediments down to -3.61 m O.D. (9.5 m b.s.) consist of "Brown and light brown, fine to medium sand, with occasional inclusions of iron-stained and iron-encrusted silty clay." No samples were taken from borehole L at this level.

However samples were taken from borehole S from 2.65 to 7.05 m b.s. (? + 3.3 to -1.1 m O.D.). All these samples are dominated by Elphidiella hannai, with strong representation of Elphidium pseudolessonii. Ammonia beccarii is usually also well-represented although not always present. These features are also characteristic of the foraminiferal assemblages of the type Bramertonian of Bramerton (Funnell et al. 1979). This is consistent with West's recognition of the Chillesford pollen assemblage (subsequently equated with the Bramertonian) in deposits at Sizewell between + 3.0 and + 4.5 m O.D. (West & Norton 1974).

(2) In borehole L the sediments between -3.61 and -18.41 m O.D. (9.5 to 24.3 m b.s.) are:"Brown, fine to coarse sand with frequent shell fragments and occasional inclusions of iron-stained and iron-encrusted silty clay." Only one sample was taken from the top of this range from borehole L. It is a relatively cold-water assemblage containing Elphidium orbiculare and Elphidium frigidum, 20% Elphidium excavatum and no Ammonia beccarii. In these respects it is very similar to the assemblage obtained at 60-80 cm in Section A of the Baventian at Covehithe, a level correlated by West (in West et al. 1980) with Ludham pollen assemblage zone 4b. West (in West & Norton 1974) also comments on the similarity of pollen from -7 to -9 m O.D. at Sizewell to the Ludham 4b (4c) assemblages. A similar foraminiferal assemblage occurs in borehole S from 8.8 to 23.6 m b.s. (? -2.8 to -17.6 m O.D.).

(3) In borehole L the sediments from -18.41 to -23.21 m O.D. (24.3 to 29.1 m b.s.) consist of:

"Grey-green, fine to medium sand with occasional shell fragments"

Foraminiferal assemblages at this depth are scarcely distinguishable from those (Bramertonian) at the top of the borehole, except that *Elphidium pseudolessonii* is rather less, and *Cibicides lobatulus* rather more abundant. Perhaps they belong to the temperate Antian Stage. The assemblages are very similar to those recorded (Funnell and West, 1962), from the Antian and lower part of the type Baventian (Ludham pollen assemblage zone 4a) at Easton Bavents. The relative lack of *Ammonia beccarii* in the Sizewell samples can be attributed to the carbon tetrachloride flotation procedures applied to them.

(4) In borehole L the sediments from -23.21 to -48.31 m O.D. (29.1 to 54.2 m b.s.) are grouped together as: "Grey-green, fine to medium sand with abundant shell fragments and occasional irregular partings and inclusions of grey silty and indurated silty clay, occasional silty, friable and weakly cemented horizons".

There are very few foraminifers at the top of this sequence between -23.9 and -24.6 m O.D.; *Elphidium frigidum* and *Elphidium pseudolessonii* are common, *Elphidiella hannai* reduced in dominance and miliolids present between -27.1 and -31.1 m O.D. which could represent a downward continuation of an Antian temperate assemblage.

At -35.0 m O.D., however, Elphidiella hannai is highly dominant (89%) and accompanied only by Cibicides lobatulus, Elphidium excavatum and Elphidium orbiculare. This could be an Arctic assemblage (? Thurnian, or just possibly Butley horizon of the Red Crag Formation, without the reworked earlier Red Crag Species found at Butley.

Below -35.0 m O.D., from -35.1 m O.D. to the bottom of the Crag deposits (the difference between the assemblages at -35.0 and -35.1 m O.D. is remarkable), there are numerous Pliocene-relict species, typical of the Red Crag formation, such as: Globulina myristiformis and other polymorphinids, Elphidium haagensis, Quinqueloculina seminulum and large Buccella inusitata, also specimens of Pararotalia serrata (which does not usually 'float' in carbon tetrachloride). Conversely Elphidium frigidum does not occur below -35.0 m O.D. A similar change takes place in the Stradbroke borehole at between -10.7 and -14.2 m O.D. at the junction (c. -15 m O.D.) between the Ludhamian (above) and the Pre-Ludhamian below (Funnell and Booth, pp.45-54, this volume). It is possible that a similar, but less well defined change also occurs near the base of the Debenham borehole at -15 to -17 m O.D.

West (in West & Norton 1974) has already noted the similarity between pollen spectra at -36 to -37 m O.D. at Sizewell and the Pre-Ludhamian of Stradbroke.

Provisional Conclusions

(a) The top of the Crag at Sizewell, down to ? -1.1 m OD. (7.05 m b.s. in borehole S) appears to be of Bramertonian age.

(b) From ? -2.8 to ? -17.6 m OD. (8.8 to 23.6 m b.s. in borehole S) foraminiferal assemblages that could represent the Baventian are present. (The sequence is thick and an intervening temperate stage could have been overlooked, i.e. unsampled, somewhere between the 8.8 and 23.6 m samples).

(c) From -19.1 to -20.1 m O.D. the foraminiferal assemblages indicate temperate conditions (? Antian).

(d) From -23.9 to -31.1 m O.D. (including 31.0 m b.s. in borehole S) the foraminiferal assemblages indicate intermediate conditions of cold (? early Antian).

(e) At -35.0 m O.D. the foraminiferal assemblages could be Arctic (? Thurnian).

(f) At -35.1 m O.D. and below the Crag Foraminifers are of Red Crag aspect corresponding to those occurring in deposits assigned to the Pre-Ludhamian stage in the Stradbroke borehole.

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Table 1: Foraminifera from Sizewell 'B' borehole L

Depth m b.s.	9.9	25.0	26.0	29.8	30.5	33.0	37.0
Depth m BOD	4.0	19.1	20.1	23.9	24.6	27.1	31.1
Total no. specimens	41	48	38	5	10	60	101
Ammonia beccarii			3				
Buccella inusitata			3				
Bulimina aculeata							
Cassidulina laevigata							
Cibicides lobatulus	2	15	26	20		10	9
Cibicides subhaidingeri							
Elphidiella hannai	56	75	47	20	80	45	49
Elphidium excavatum	20	2	3	40	20	18	16
Elphidium frigidum	5	4	5			12	10
Elphidium haagensis							
Elphidium margaritaceum	7						
Elphidium orbiculare	2						
Elphidium pseudolessonii	7	2	3			10	12
Elphidium willimasoni						2	
Elphidium sp.							1
Faujasina subrotunda							
Fissurina							
Globulina myristiformis							
Guttulina							
Lagena							
Lenticulina							
Nonion							
Pullenia sphaeroides							
Polymorphina			8	20			
Pyrgo							
Pyrulina							
Pararotalia serrata							
Rosalina						1	
Quinqueloculina seminulum		2					1
Quinqueloculina			3			2	3
Textularia suttonensis							

40.9	41.0	41.1	42.2	43.3	43.8	43.9	44.1	44.7	45.8	50.8	53.7	53.8
35.0	35.1	35.2	36.3	37.4	37.9	38.0	38.2	38.8	39.9	44.9	47.8	47.9
63	96	76	14	16	98	60	115	54	95	1	64	29
	1				2		1				2	
		1			2	2		4	2		6	
							1					
		1					1	2				
6	14	3	21	19	16	27	26	30	19		8	3
					1							
89	69	71	43	38	54	43	44	39	60	100	42	52
3	4	8		25	7	10	8	7	2		13	10
		1				3	1		2			3
					2	3	5	7	1		2	7
2												
	1	1					1		1			
						2						3
					2						5	
						2					2	
						2	1					
	1	4	14		3		2	2	2		2	
	2	1		13	2	5	3	2	2		8	3
	1	1						2	1			3
		1				2						
					1						2	
							1					
												3
					1						2	
			7					2	2			
			14									
								2			3	
	4	7		6	3	2	5		5		3	7
	2					2					3	3
								2				

Table 2: Foraminifera from Sizewell 'B' borehole S

Depth m b.s.	2.65	2.8	3.0	3.2	4.2	5.1	7.05	8.8	12.2	23.6	31.0
Depth m BOD (estimated)	+3.3	/+3.2	/+3.0	/+2.8	/+1.8	/+1.9	/-1.1	-2.8	/-6.2	/-17.5	-27.0
Total no. specimens	42	75	80	14	153	61	20	68	36	33	10
Ammonia beccarii	12	7	11		11		5	6	3		
Buccella inusitata								1			
Cassidulina laevigata										3	
Cibicides akneriana						2					
Cibicides lobatulus		3	1		6	16	20	3	3		20
Cibicides subhaidingeri									3		
Elphidiella hannai	76	73	66	79	48	72	55	76	58	64	80
Elphidium excavatum	2	3	8	7	7			1	8	3	
Elphidium frigidum	2	3			3	3	10	1	8	18	
Elphidium margaritaceum		3	3		8			3	3	3	
Elphidium orbiculare								1		6	
Elphidium pseudolessonii	5	8	8	7	16	3	10	3	11		
Elphidium williamsoni			3		1	2					
Lagena				7							
Nodosaria									3		
Pullenia sphaeroides								1			
Quinqueloculina seminulum										3	

Bull. geol. Soc. Norfolk, 33, 63-72

AN INTERGLACIAL SITE AT GALLEY HILL, NEAR ST. IVES, CAMBRIDGESHIRE

R.C. Preece* and P.A. Ventris*

Abstract

Plant and molluscan fossils collected by Mr. P.G. Cambridge from an organic silt in a gravel pit at Galley Hill, near St. Ives, Cambridgeshire, have been analysed. These suggest that the silts were deposited by a large, sluggish stream with a wide open floodplain, during the early temperate phase of the Ipswichian interglacial (Ip II). The presence of some woodland within the catchment is indicated by the occurrence of macrofossils of forest taxa including *Acer monspessulanum*. The Mollusca include an abundant aquatic fauna and an assemblage characteristic of calcareous grassland, including the extinct helicellid *Candidula crayfordensis*. The first fossil record of the moss *Entodon concinnus* is discussed.

The overlying gravels, cryoturbated in the upper metre, are interpreted as Devensian in age.

Introduction

During 1963, West End Pit was opened for gravel extraction a short distance west of the Galley Hill crossroads, about 2.5 miles south of St. Ives (TL 305 685). Numerous large mammal bones and teeth were collected from discarded material at the washing plant. Mr.P.G. Cambridge visited the locality at this time and published two short notes giving details of the stratigraphy and a preliminary account of the fossils (Cambridge, 1965; Forbes & Cambridge, 1967). A measured section of the west face of the pit is given by Cambridge (1965). These measurements have been used to construct Figure 1, which shows an organic deposit lying below about 3.5m of gravel, with laterally impersistent clay bands. The upper 1.2m of the gravels were involuted and probably cryoturbated. This

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sequence has been interpreted as an interglacial channel fill (possibly Ipswichian) below a succession of cold stage fluvial gravels and sands. The Institute of Geological Sciences have visited several pits in this area and record that the upper metre of gravel is invariably decalcified (Edmonds & Dinham, 1965). The surface of the gravels forms an extensive terrace of the River Ouse. At Galley Hill this surface is at about 6.4m above O.D., which means that the organic horizon lies at about 3m O.D.

Recently, partially sorted material from the Galley Hill organic beds was passed to us by Mr.P.G.Cambridge, for study. This note presents a list of the plant macrofossils and Mollusca present.

The samples had been wet sieved using a 1mm sieve so that the smaller seeds (e.g. Typha and Juncus) and the smaller shells were absent. This fact prohibits anything but the broadest palaeoecological interpretations to be made. The figures and percentages quoted should therefore be treated with caution. Nevertheless, the discovery of several interesting fossils has prompted the preparation of this report.

Macroscopic plant remains

Plant macrofossils had been extracted from the sediment and dried by Mr. P.G. Cambridge before being passed to P.A.V. for identification. The preservation of the remains was rather poor and much of the fine sculpturing of the macrofossils had been lost. Nevertheless, a total of 126 plant macrofossils, representing a minimum of 26 taxa were identified. The results are presented in Table 1. Nomenclature follows Clapham, Tutin and Warburg (1962).

The depositional environment is well reflected in the macrofossil assemblage. Altogther 65% of the identified remains are of fully aquatic plants. Scirpus sp. and Ranunculus sardous are also associated with damp ground. This assemblage indicates that the organic sediments were deposited by a slow flowing river. Potamogeton spp., which usually prefers slow flowing water, dominates. Ceratophyllum demersum, a plant that lacks roots and rhizomes and would therefore be washed away very easily in fast flowing water is also abundant. Haslam (1978) states that

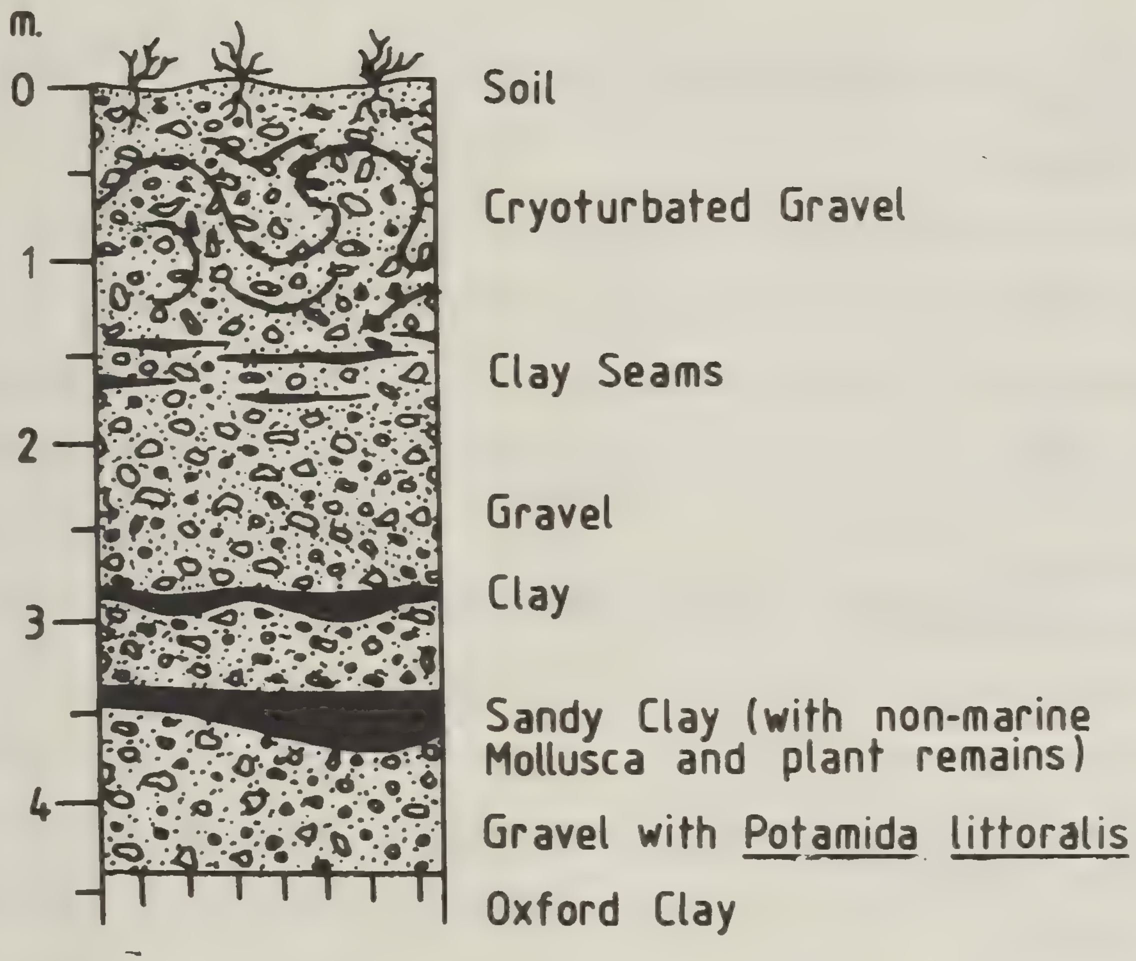
m.
0
1
2
3
4
Soil
Cryoturbated Gravel
Clay Seams
Gravel
Clay
Sandy Clay (with non-marine Mollusca and plant remains)
Gravel with Potamida littoralis
Oxford Clay

Fig. 1 Stratigraphy of West End Pit Galley Hill.

Table 1 Galley Hill Plant Macrofossils

TREES	
Pinus L.	6 seeds
Acer campestre L.	3 samarae
Acer monspessulanum L.	11 samarae
Acer L. indet.	6 samarae
SHRUBS	
Rubus L. sp.	2 fruit stones
Prunus spinosa L.	2 fruit stones
Prunus cf. *padus* L.	3 fruit stones
HERBS (SHADE)	
Stachys sylvatica L.	1 seed
HERBS (OPEN GROUND)	
Ranunculus repens L.	3 achenes
Agrimonia eupatoria L.	4 fruits
HERBS (OPEN GROUND-WET)	
Ranunculus sardous Crantz	1 achene
AQUATICS	
Nymphaea alba L.	10 seeds
Nuphar lutea (L.) Sm.	9 seeds
Ceratophyllum demersum L.	26 fruits
Oenanthe aquatica (L.) Poir	2 fruits
Potamogeton L. spp.	30 pyrenes
Zannichellia palustris L.	1 seed
Sparganium erectum L.	1 fruit stone
Sparganium angustifolium Michx.	1 fruit stone
Sparganium minimum Wallr.	2 fruit stones
UNCLASSIFIED	
Viola L. sp	1 seed
MOSS FRAGMENTS	
Homalothecium cf. *lutescens* (Hedw) Robins	
Hypnum cupressiforme Hedw.	
ALGAE	
Many *Chara* oospores	

C. demersum is one of the aquatic species most closely associated with negligible flow. The only umbellifer found, Oenanthe aquatica, is also found today in slow moving or stagnant water. An interesting record is Najas marina, a rare plant in Britain today which is now restricted to mildly brackish habitats in Norfolk. However, in Europe it also occurs in freshwater habitats, as it obviously did at Galley Hill.

The terrestrial taxa present provides evidence for both woodland and areas of open ground within the river catchment. From the macrofossil evidence it appears that both Pinus and Acer were important members of the local forest community. It is likely that the 6 unidentified samarae are degraded examples of A. campestre or A. monspessulanum rather than fruits of another species. The woodland understory included Rubus and Prunus species, and a ground flora of shade tolerant herbs such as Stachys sylvatica.

The areas of open ground indicated by Ranunculus and Agrimonia either represent clearings within the woodland or more likely, the floodplain of the river.

The following additional species have also been recorded from the organic silts (Cambridge, 1964; Cambridge, 1965).

Potamogeton natans L. - pyrene
Fraxinus excelsior L. - wood
Quercus robur L. type - wood
Entodon concinnus (De Not.) Paris - moss fragment.

The occurrence of the moss Entodon concinnus (Cambridge, 1968) is particularly noteworthy since it represents the only known record in the British Pleistocene. Dickson (1973) reports that the solitary fragment was well preserved and notes that E. concinnus has a widespread but scattered distribution throughout Europe, where it favours calcicolous grassland. It has been recorded from several deposits of Weichselian age in Poland.

The macrofossil assemblage at Galley Hill, with the Mediterranean and central European Acer monspessulanum, is clearly of interglacial character.

Non-marine Mollusca

A rich molluscan fauna was preserved in the organic silts. A total of 24 freshwater and 15 terrestrial species were identified amongst the sieved residues (see Table 2).

Table 2

FRESHWATER SPECIES

- *Valvata cristata* Müller
- *Valvata piscinalis* (Müller)
- *Belgrandia marginata* (Michaud)
- *Bithynia tentaculata* (L.)
- *Lymnaea palustris* (Müller)
- *Lymnaea stagnalis* (L.)
- *Lymnaea peregra* (Müller)
- *Planorbis planorbis* (L.)
- *Anisus leucostoma* (Miller)
- *Anisus vortex* (L.)
- *Anisus vorticulus* (Troschel)
- *Gyraulus laevis* (Alder)
- *Armiger crista* (L.)
- *Hippeutis complanatus* (L)
- *Acroloxus lacustris* (L.)
- *Sphaerium corneum* (L.)
- *Sphaerium lacustre* (Müller)
- *Pisidium amnicum* (Müller)
- *Pisidium casertanum* (Poli)
- *Pisidium milium* (Held)
- *Pisidium subtruncatum* Malm
- *Pisidium henslowanum* (Sheppard)
- *Pisidium nitidum* Jenyns
- *Pisidium moitessierianum* Paladilhe

LAND SPECIES

- *Succinea oblonga* Draparnaud
- *Oxyloma pfeifferi* (Rossmässler) OR *Succinea putris* (L.)
- *Cochlicopa lubrica* (Müller)
- *Truncatellina cylindrica* (Férussac)
- *Vertigo pygmaea* (Draparnaud)
- *Vertigo angustior* Jeffreys
- *Pupilla muscorum* (L.)
- *Vallonia costata* (Müller)
- *Vallonia pulchella* (Müller)
- *Vallonia enniensis* (Gredler)
- *Vallonia excentrica* Sterki
- *Acanthinula aculeata* (Müller)
- *Deroceras*/*Limax*
- *Candidula crayfordensis* (Jackson)

Many common smaller species (e.g. Punctum pygmaeum) were probably lost as a result of the coarse sieve (1mm) used. It would therefore be very misleading to give absolute frequencies.

The rich aquatic assemblage is typical of interglacial faunas described elsewhere in eastern England. Belgrandia marginata is extinct in Britain today but still survives in parts of southern France. In Britain it is a characteristic interglacial indicator. The aquatic fauna is indicative of a sizeable, sluggish stream with a rich aquatic vegetation.

The terrestrial fauna consists predominantly of xerophilous species typical of calcareous open grassland. Such species include Truncatellina cylindrica (rare in Britain today), Vertigo pygmaea, Pupilla muscorum, Vallonia costata, Vallonia excentrica and Candidula crayfordensis.

Candidula crayfordensis, represented by four shells, is an extinct helicellid snail not unlike C. intersecta, (Kennard & Woodward, 1922, fig. 34) and, like the family as a whole, is thought to have lived in dry calcareous grassland. In Britain it has been recorded from sites of Hoxnian age at Swanscombe and Clacton (Kerney, 1971) and from sites of supposedly Ipswichian age at Crayford, Erith, Ilford, Brentford and various sites in the vicinity of Cambridge (Kennard & Woodward, 1922).

The remainder of the terrestrial fauna consists of hygrophilous species such as would be expected in the margins of a river floodplain.

Vertebrates

The following vertebrate remains have been recorded from the Galley Hill excavations by Forbes and Cambridge (1967). The nomenclature follows Stuart (1982).

Ursus sp. (Bear)
Palaeoloxodon antiquus Falconer & Cautley (Straight-tusked elephant)
Mammuthus sp. (Mammoth)
Coelodonta antiquitatis Blumenbach (Woolly rhinoceros)
Megaceros sp. (Giant deer)
Dama dama (L.) (Fallow deer)

Cervus elaphus L. (Red deer)

Bos primigenius Bojanus (Aurochs)

This list comprises species typical of both interglacial (e.g. *Palaeoloxodon* and *Dama*) and cold stage conditions (e.g. *Coelodonta*) and would therefore appear to be mixed. It is probable that these vertebrate remains were present both in the channel fill sediments and the overlying gravels.

Conclusions

Although neither author visited the sections, field notes made by Mr. P.G. Cambridge enabled us to interpret the stratigraphy. The water table prevented the basal contact between the Pleistocene gravels and the Oxford Clay from being examined. However, gravel dredged from below the water table contained the bivalve *Potamida littoralis*, known only from interglacial deposits in Britain.

The depositional environment of the organic silts appears to have been a slow flowing backwater of a river, which received contributions from both woodland and herb-dominated floodplain communities. To judge from the total fossil assemblage, these silts were clearly deposited during an interglacial period.

The presence of *Acer monspessulanum* with *Belgrandia marginata* and *Anisus vorticulus* suggests an Ipswichian date. *A. monspessulanum* is present in deposits of Ipswichian zone II age at other sites in eastern England (Phillips, 1974) and this date is suggested for the Galley Hill organic beds.

The frequent occurrence of *Acer monspessulanum* macrofossils in the Ipswichian had led to a debate on whether or not the high pollen frequencies for *Acer* in the Ipswichian are due to the additional occurrence of this species. The highest frequencies of *Acer* pollen are found in Ipswichian zone IIb (West, 1980), and are often associated with macrofossils of *A. monspessulanum*. At Wing however the levels of high *Acer* pollen contained only *A. campestre* macrofossils (Hall, 1980). Phillips (1974) has attributed the widespread occurrence of the open scrub species *A. monspessulanum* to the abundance of river valley sediments preferentially preserving the vegetation adjacent to the floodplains. This contrasts with enclosed lake basin sites where forest may be expected to fringe the water body.

The age of the overlying gravels is not clear from the notes but was almost certainly deposited during the succeeding Devensian cold stage because fluvial gravels characterise cold stage deposits in south-east England (Castleden, 1980). The bones of Coelodonta probably came from this level. Unfortunately no samples of the clay seams within the gravels were collected. The involutions, of probable periglacial origin, that distort the upper metre of the gravel must presumably also be of Devensian age.

Appendix

Whilst sorting the material for Mollusca, six ostracod values were discovered. Dr. J.E. Robinson kindly identified these as:

Herpetocypris reptans (Baird) - Five valves

Candona neglecta Sars - One valve

These species indicate quiet, plant-rich waters and a soft substrate. Smaller specimens were undoubtedly lost as a result of the coarse sieving.

Acknowledgements

We are greatly indebted to Mr. P.G. Cambridge for passing the material to us. A series of mollusc and plant specimens have been deposited in the P. Cambridge collection, Sedgwick Museum, Cambridge. Dr. C. Turner and Mrs. M. Pettit freely gave advice on some critical plant macrofossils and Dr. A.M. Alderton indentified the moss fragments. We are grateful to Dr. J.E. Robinson for identifying the Ostracoda. We thank Professor R.G. West and Dr. P.L. Gibbard for reading the manuscript and for helpful discussion.

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VERTEBRATES FROM A NEW SITE AT COSTON, NORFOLK

J.L. Lightwing*

Summary

This paper describes the vertebrate fauna from a new interstadial site at Coston, Norfolk. A detailed description of the stratigraphy and palaeobotany of the site, and possible correlation with other sites in Britain and Europe is in preparation by Dr. A.J. Stuart and Dr. P.I. Gibbard of Cambridge University.

Introduction

The site was worked temporarily by Atlas Aggregates for the extraction of sand and gravel. It is situated in the Yare Valley at Coston (TG 063065). The gravels are approximately 0.3 metres below topsoil and are between 7 and 8 metres thick, approximately 1m of which was seen, resting on an organic silt bed. The vertebrate remains were collected mainly from the top of the silt bed, with a few coming from the lower gravels. The small vertebrate remains were collected by wet sieving through a 1 mm sieve.

Description of Specimens

Fish remains

The fish remains consist of two scales, both of which closely resemble those of the modern perch, *Perca fluviatilis*.

Amphibia

The amphibian remains consist of a single indeterminate limb bone fragment, probably attributable to the common frog, *Rana temporaria*.

Mammalia

Mammal remains belonging to five separate orders are recorded from this site.

Rodentia

Several small teeth and limb bones were recovered from sieving. Of these the vast majority are of voles, of which one upper incisor and one lower molar

---

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are identified as water vole *Arvicola terrestris*, and field vole *Microtus agrestis*.

Canis lupus L. (wolf)

The wolf remains found consist of two cervical vertebrae. One, which had been dredged, author's collection (J.L./Cos. 162) is a complete cervical (4th to 7th) vertebrae. The second specimen (J.L./Cos. 215) is in an incomplete vertebra, with the centrum missing. This specimen was found *in situ* in the silt bed.

Ursus sp. (bear)

A fine lower canine tooth (J.L./Cos 53) is the only record of bear from the site. This specimen was dredged.

Order *PROBOSCIDEA*

Mammuthus primigenius Blumenbach (mammoth)

Several bones and tusk fragments have been found which are attributable to woolly mammoth. Unfortunately only one molar, an incomplete lower unerupted specimen (J.L./Cos. 276) is possitively identified. The other remains include a rear section of a skull (from the gravels), a humerus (dredged) and the centrum of a vertebra (also dredged) also presumed to be mammoth.

Order *ARTIODACTYLA*

Bison priscus Bojanus (bison)

Several incomplete skulls, horn cores, jaws, limb bones and vertebrae have been found which are attributed to bison. Skulls and horn cores are the commonest finds. The other bones include humeri, radii, femora, a scapula, ribs, metapodials phalanges and vertebrae.

Rangifer tarandus L. (reindeer)

The reindeer remains are mainly antlers. A few vertebrae have also been found. These remains all come from the lower gravels and silt bed.

Cervus elaphus L. (red deer)

Red deer remains are rare compared with reindeer. The only record is an incomplete left shed antler (dredged). Specimen number (J.L./Cos. 115).

Hippopotamus amphibius L. (hippopotamus)

Only one specimen, a lower incisor can be attributed to hippopotamus. This is assumed to be derived from earlier deposits. Specimen number (J.L./Cos. 56).

Order PERISSODACTYLA

Coelondonta antiquitatis Blumenbach (woolly rhinoceros)

The woolly rhinoceros material consists of a fine complete dredged skull and an associated lower jaw. (Specimen number J.L./Cos. 194). The skull is almost complete, although all the teeth and part of the palate is missing. Otherwise the skull is in a very good state of preservation. The jaw found with the skull appears to belong to the same animal. The right mandible has part of the condyle and the second premolar missing. The back of the left mandible is missing to the back alveolus of the first molar, and the second premolar is also missing.

Comments

The occurrence of land and freshwater shells and plants found in the silts suggest that they were deposited in the valley of a slow moving river. Probably the larger mammals were supported by grazing the floodplain and browsing nearby forests. A preliminary analysis by Dr. A.J. Stuart and others at Cambridge University indicates that the age of the beds could be correlated with the early Devensian "Chelford Interstadial" (A.J. Stuart, personal communication). If this is the case then this is the first record of a fauna of this age in Britain.

The fauna is notable for the several near complete skulls and in one case an associated mandible, indicating that many of the animals must have died close to the deposition site.

The fact that reindeer, woolly rhinoceros and woolly mammoth occur suggest a cold climate, although the finding of a hippopotamus tooth suggests that more than one fauna is represented as the hippopotamus is unlikely to occur in anything but an interglacial fauna. It is quite possible that the younger and colder, early Devensian beds are channelled into older and warmer (?) Ipswichian deposits.

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Footnote

Since this paper was first written another pit has been worked on this site and has produced more vertebrate remains generally associated with Ipswichian Interglacial deposits, namely: *Palaeoxodon antiquus* (Falconer and Cautley) straight tusked elephant, *Hippopotamus amphibius* L. hippopotamus along with bison and giant deer.

Draft received April 1981; revised April 1983.

Table 1: Coston Vertebrates

Key to Table

Reference to collections: (J.L.) = Author, (N.C.M.) = Norwich Castle Museum

Frequency of occurrence: VR = very rare, R = rate 2-8, C = common 8-20, A = abundant 20+

Type of remains: sk.= skull, md. = mandible, a. = antler, t. = teeth, tu.= tusk, l. = limb bones, v. = vertebra, s. = scale

Position: IS = *in situ* in silt, DR = dredged, G = from gravels

	Frequency	Type of remains	Position	Collection
PISCES				
Perca sp.	VR	s.	IS	(J.L.)
AMPHIBIA				
Rana sp.	VR	l.	IS	(J.L.)
MAMMALIA				
RODENTIA				
Microtus agrestis L.	R	t.	IS	(J.L.)
CARNIVORA				
Canis lupus L.	R	v.	IS	(J.L.)
Ursus sp.	VR	t.	G	(J.L.)
PROBOSCIDEA				
Mammuthus primigenius Blum.	C	t.tu.sk.	G	(J.L.)
PERISSODACTLYA				
Coelodonta antiquitatis Blum.	R	sk.md.l.	G	(J.L.)
ARTIODACTYLA				
Bison priscus Bojanus	A	sk.md.t. l.v.	IS	(J.L.) (N.C.M.)
Rangifer tarandus L.	C	sk.a.l.v.	IS	(J.L.)
Cervus elaphus L.	R	a.v.	G	(J.L.)
Hippopotamus sp.	VR	t.	G	(J.L.)

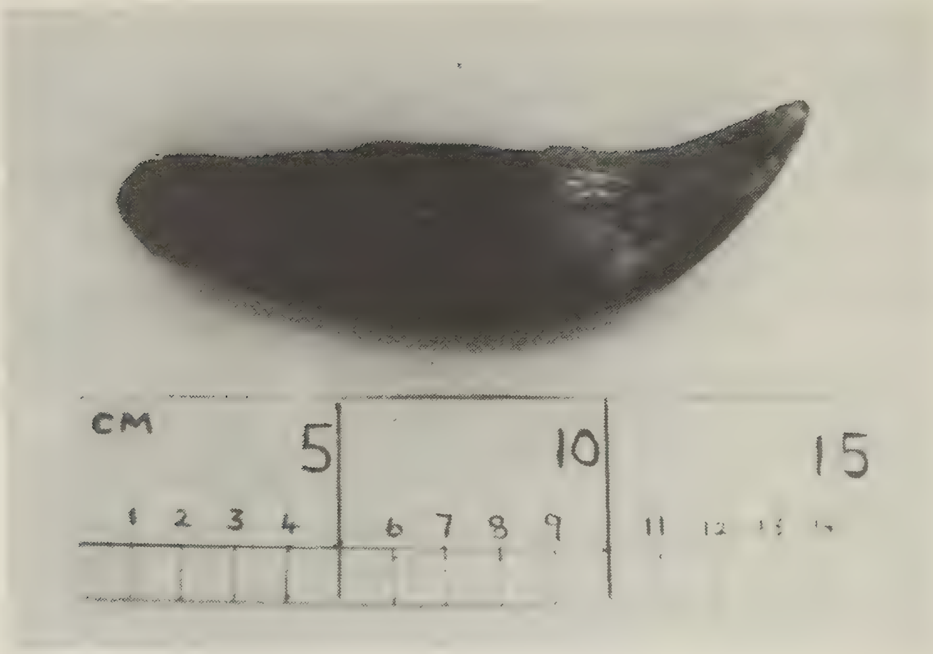

Plate 1. *Ursus* sp., a bear (JL/COS53) - lower canine (overall length 124 mm, length of crown 53 mm, width at base of crown 31 mm).

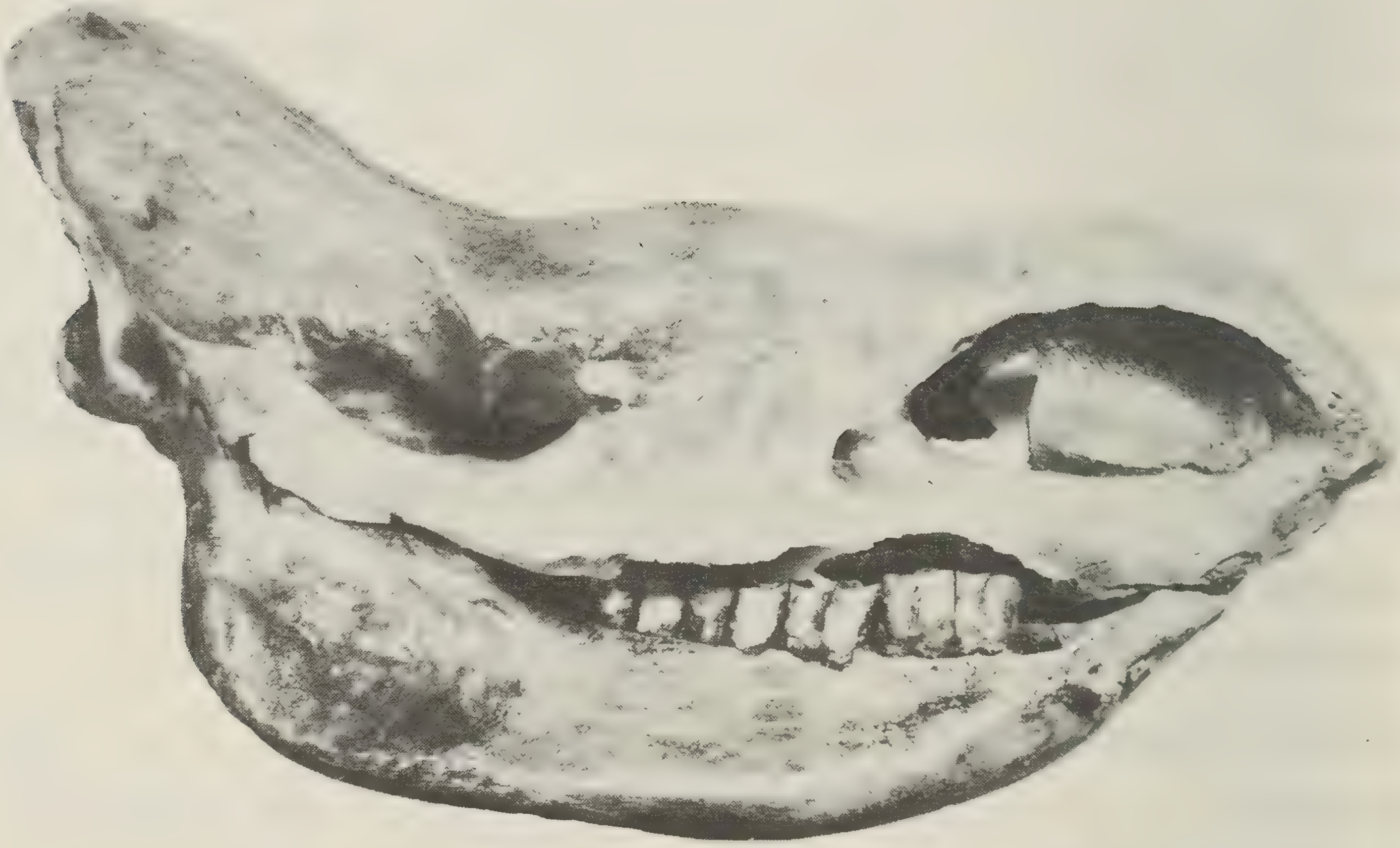

Plate 2. *Coelodonta antiquitatis*, woolly rhinoceros (SL/COS194) - skull and mandible. (Skull: overall length 735 mm, overall width 315 mm, height 245 mm, width across nasal bone 138 mm; right mandible: overall length 523 mm, height of ramus at P_4-M_1, 80 mm, height of ramus at rear of M_3 107 mm; teeth - right jaw: P_2 missing, P_3 length 32 mm, height 32 mm, width 19mm, P_4 35, 37, 32 mm, M_1 45, 35, 25 mm, M_2 51, 29, 25 mm, M_3 49, 31 23 mm; left: P_2 missing, P_3).

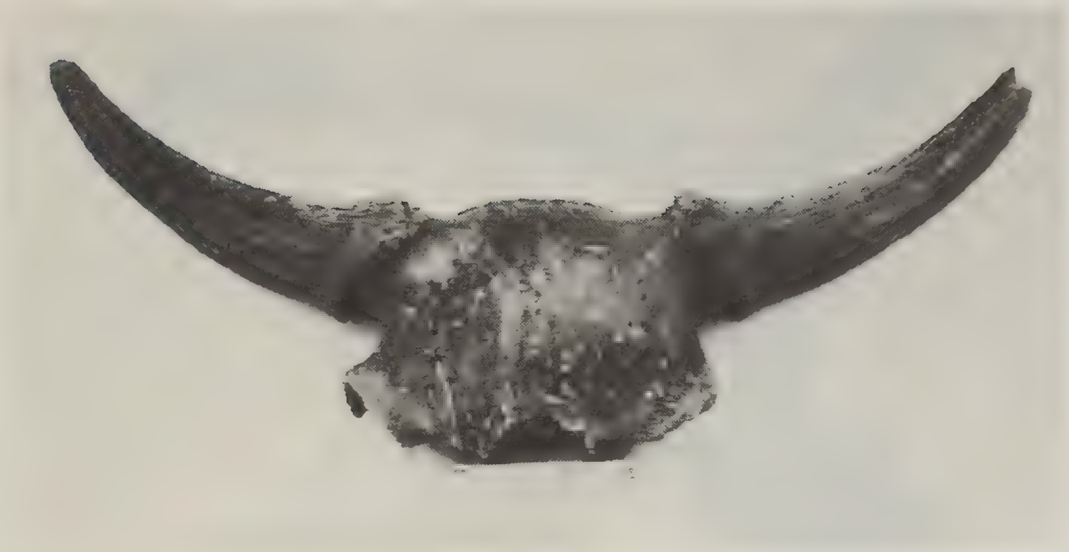

Plate 3. Bison priscus, bison (JL/COS253) (Between horn tips 880 mm, between horn core bases 220 mm, left horn core length along outer curvature 390 mm, right horn ditto 300 mm, circumference at base of left horn core 430 mm, ditto right horn core 410 mm)

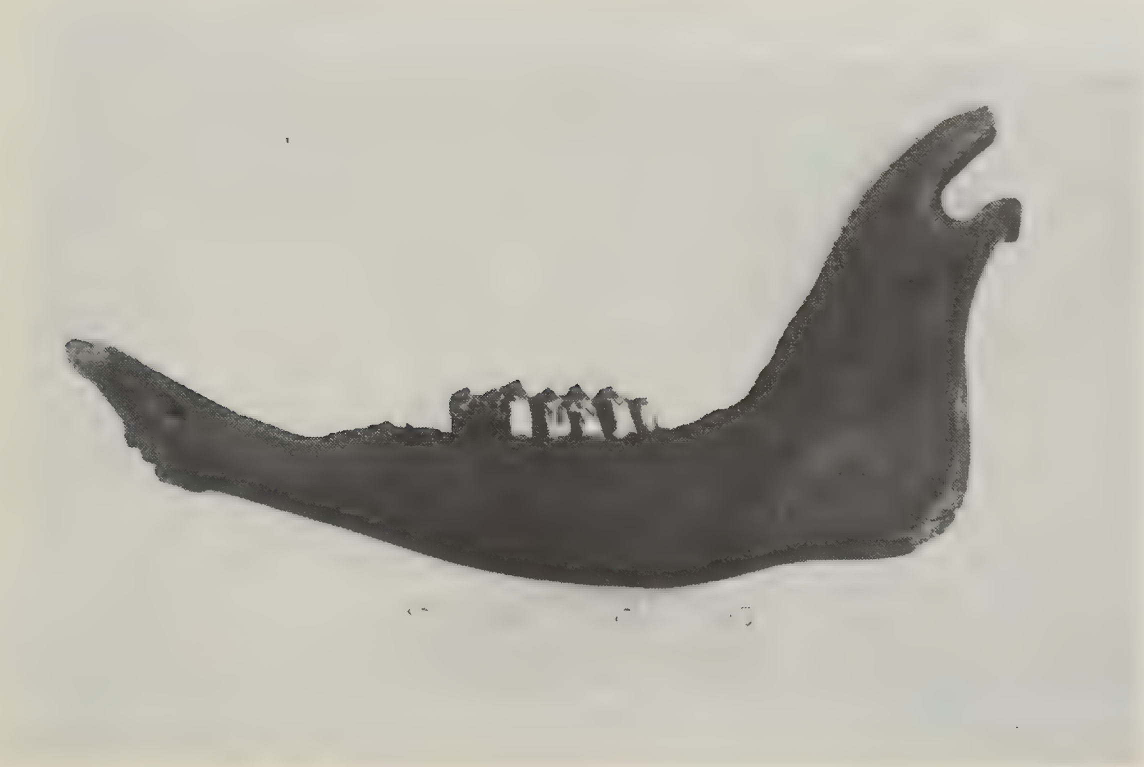

Plate 4. Bison priscus - bison (JL/COS192) left lower jaw

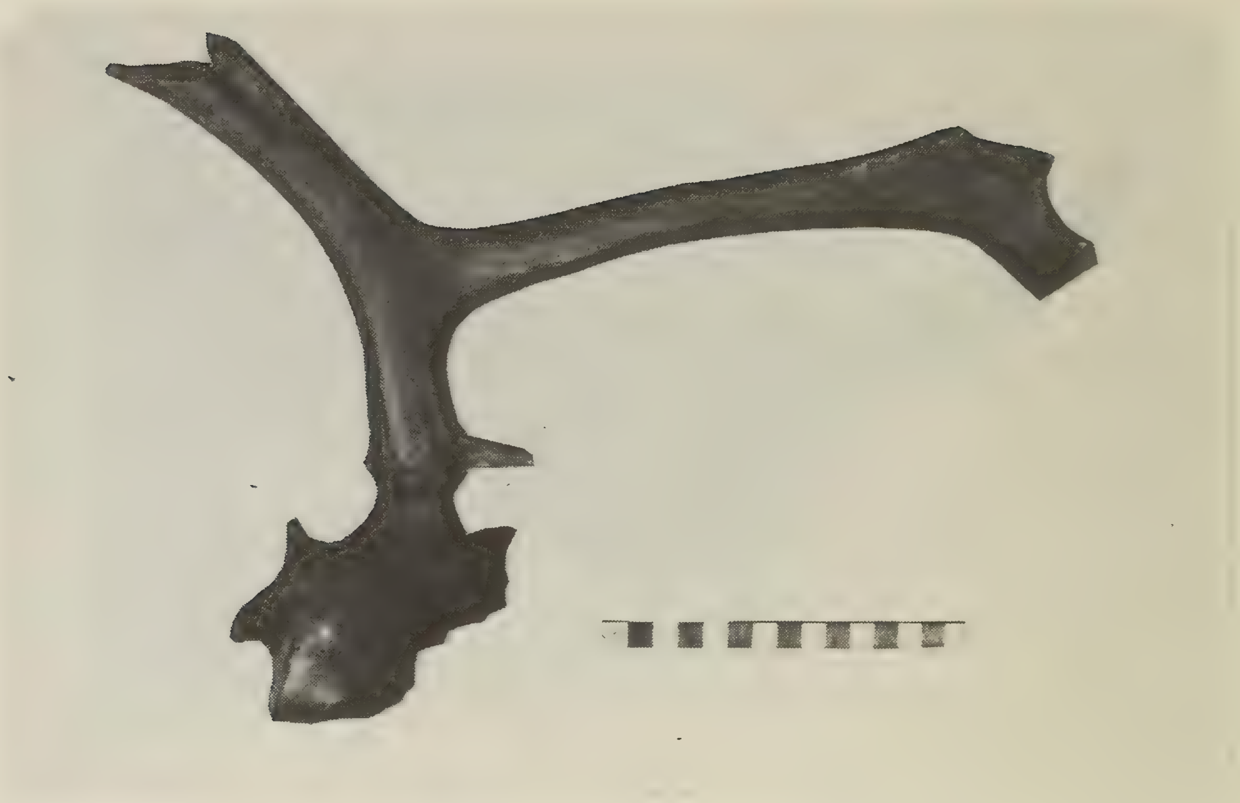

Plate 5. Rangifer tarandus, reindeer (JL/COS169) skull and antler

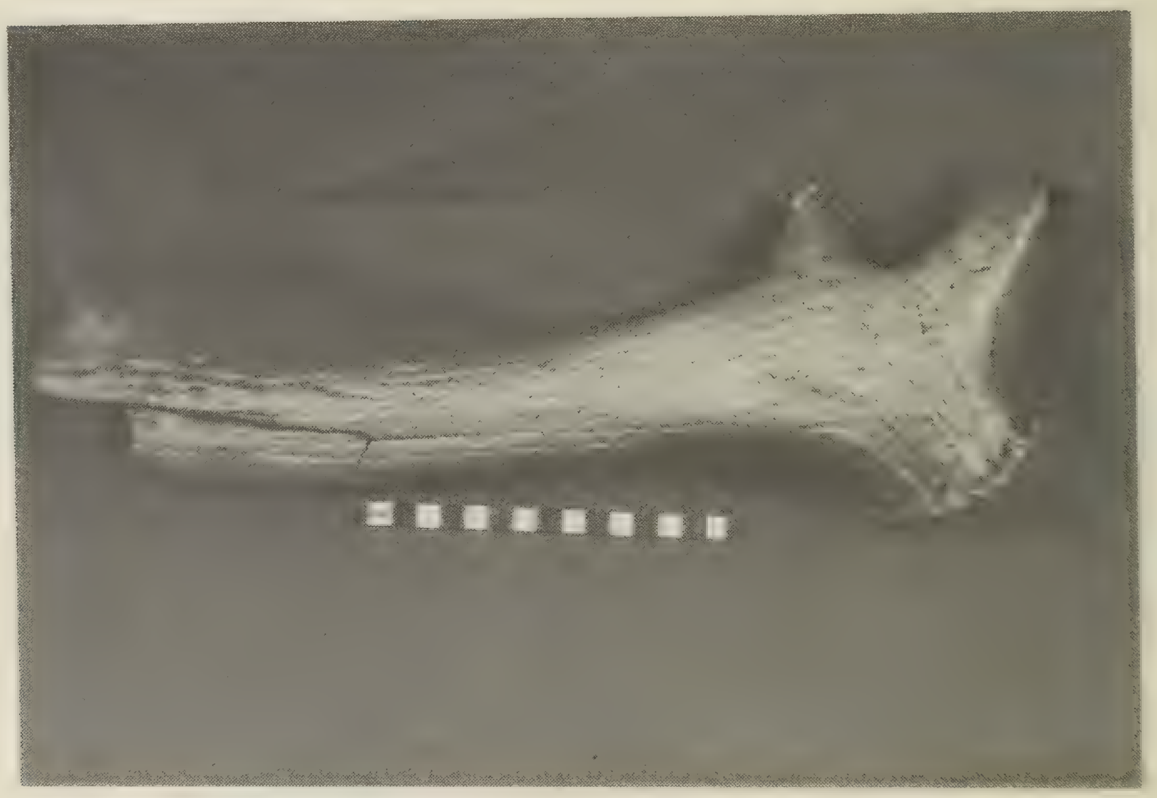

Plate 6. Cervus elaphus, red deer (JL/COS115) shed antler

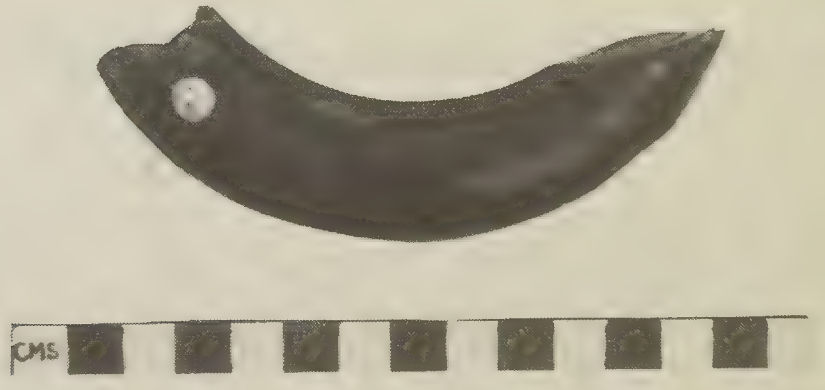

Plate 7. Hippopotamus amphibius (JL/COS56) incisor

CONTENTS

		Page
Editorial		1
Andrews, J.	A faunal correlation of the Hunstanton Red Rock with the contemporaneous Gault Clay, and its implications for the environment of deposition	3
Whittlesea, P.S.	Observations on the stratigraphical range and morphology of the Cretaceous cribrimorph Bryozoan: *Ubaghsia crassa* (Lang)	27
Whittlesea, P.S.	The occurrence of the Brachiopod genus *Rugia* Steinich in the Norwich Chalk	32
"Collecting at Bulcamp July 1979"		34
Funnell, B.M.	The Crag of Bulcamp, Suffolk	35
Funnell, B.M. & Booth, S.K.	Debenham and Stradbroke, two Crag boreholes compared	45
Funnell, B.M.	Preliminary note on the Foraminifera and stratigraphy of C.E.G.B. Sizewell boreholes L & S	54
Preece, R.C. & Ventris, P.A.	An interglacial site at Galley Hill, near St. Ives, Cambridgeshire	63
Lightwing, J.L.	Vertebrates from a new site at Coston, Norfolk	73

The Geological Society of Norfolk exists to promote the study and knowledge of geology, particularly in East Anglia, and holds monthly meetings throughout the year.

Visitors are welcome to attend the meetings and may apply for membership of the Society. For further details write to the Secretary: Miss Diana Smith, Castle Museum, Norwich NR1 3JU.

Copies of the Bulletin may be obtained from the Secretary at the address given above; it is issued free to members.

The illustration on the front cover is taken from Figure 43 (page 514) of Lyell's "Principles of Geology", 1867 Edition, and shows the "Tower of the buried church of Eccles, Norfolk, A.D. 1839".

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Late Jurassic – Mid Cretaceous of Norfolk
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Glacial geology of Norfolk
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BULLETIN of the GEOLOGICAL SOCIETY OF NORFOLK

No. 34 December 1984

Editor: B.M. Funnell, School of Environmental Sciences
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EDITORIAL

meeting

The British Association for the Advancement of Science met at the University of East Anglia in Norwich during September 1984. A full and well attended geology programme of lectures, exhibitions and excursions was arranged by Section C, to which the British Geological Survey made a substantial contribution.

Bulletin No. 34 consists of four articles written to provide a background to the geological excursions organised in connection with the BA meetings. Taken together they comprehensively summarise recent work on the late Jurassic to mid Cretaceous, Pliocene to early Pleistocene, Glacial and Post-Glacial deposits of Norfolk and parts of Suffolk. The British Geological Survey have provided a major part of these articles, which incorporate the results of much recent Geological Survey work in Norfolk and Suffolk. Your editors are especially grateful to members of the Geological Survey for finding time to make such a considerable contribution at a time of particular organisational difficulty. We are also much indebted to Barbara Slade (secretary) and David Mew (cartographer) of the School of Environmental Sciences for their unstinting help in preparing this Bulletin for printing, including help with the design of the Geological Society of Norfolk's new logo, which appears on the cover alongside the logo for the BA meeting at Norwich, itself reproduced by permission of the University of East Anglia. Bulletin No. 34 may not entirely replace "The Geology of Norfolk", which was published on the occasion of the 1961 BA meetings in Norwich, (it lacks altogether a contribution on the Chalk), but it should go a long way towards it.

It is intended that Bulletin No. 35, consisting of a range of submitted papers, will be published in April 1985. Authors are reminded that the Bulletin of the Geological Society of Norfolk exists to publish research papers, notes, and general or review articles relevant to the geology of East Anglia as a whole, and does not restrict consideration to items concerning the geology of Norfolk alone. Articles can be submitted to either Editor at any time. All papers are normally refereed.

Potential contributors should note that although we prefer manuscripts to be submitted in typewritten copy we will accept neatly handwritten material. It is most helpful if the style of the paper, in terms of capitalization, underlining, punctuation, etc., is made to conform strictly to those normally used in the Bulletin. All measurements should be given in metric units. The reference list is the author's responsibility and should always be carefully checked.

Illustrations are important. They should be drawn with thin dense black ink lines. Thick lines, close stipple or patches of solid black should be avoided as these tend to spread in the printing process usually employed. Original illustrations should, before reproduction, fit into an area of 175 mm by 225 mm. Full use should be made of the first (horizontal) dimension, which corresponds to the width of print on the page, but the second (vertical) dimension is an upper limit only. Half-tone (photographic) plates can also be accepted, providing the originals exhibit adequate contrast, and when their use is warranted by the subject matter.

B.M. Funnell
P.G. Cambridge

Bull. geol. Soc. Norfolk, **34**, 3-64 December 1984

THE LATE JURASSIC TO MID CRETACEOUS ROCKS OF NORFOLK

R.W. Gallois*

INTRODUCTION

The Upper Jurassic and Lower Cretaceous rocks of Norfolk crop out in a strip of low-lying ground 20 to 40 km in width running through the western part of the county from Hunstanton to the River Little Ouse, a distance of about 60 km. They are composed almost entirely of soft mudstones and loose sands and are deeply weathered at outcrop; there is only one natural exposure (Hunstanton cliffs) in the area. Much of the outcrop is concealed beneath the thick Holocene deposits of Fenland and The Wash or beneath Pleistocene deposits. However, the structure of the area is simple and this has enabled the stratigraphy to be worked out in recent years by means of field surveys and the examination of temporary sections and continuously cored boreholes. The sequence falls naturally into three parts - the almost wholly argillaceous Upper Jurassic Kimmeridge Clay and Lower Cretaceous Gault separated by the predominantly arenaceous top Jurassic-Lower Cretaceous Sandringham Sands, Dersingham Beds, Roach and Carstone.

The Kimmeridge Clay of Norfolk is composed of shelly mudstones with a rich fauna. Variations in the local stratigraphy, the mineralogy of the formation and its lithological and faunal associations suggest that it was deposited on a broad marine shelf, in warm, relatively shallow, quiet water, close to a land area (the London Platform).

Widespread earth movements, related to the separation of Europe and Africa from the Americas, occurred in the late Jurassic in

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northwest Europe. In Norfolk, they caused the Kimmeridge Clay to be uplifted and eroded, the amount of erosion being greatest adjacent to the London Platform. Marine conditions returned to the county in the latest Jurassic (Volgian) but gave rise to predominantly arenaceous sediments; this change probably reflects a rejuvenation of the land areas that supplied the siliciclastic fraction of the Kimmeridge Clay. The succeeding Lower Cretaceous deposits are composed largely of variable amounts of sand, clay and chamosite/limonite oolites with lesser amounts of glauconite, pebbles and siderite mudstone. The lithologies, sedimentary features and faunas indicate deposition in a variety of shallow, near-shore marine environments. Renewed earth movements occurred in the mid Cretaceous (Aptian and Albian) but, although they caused considerable erosion of the Lower Cretaceous sequences close to the London Platform, they probably had little effect on sedimentation further west in Norfolk. Argillaceous sediments, closely similar to the Kimmeridge Clay, were deposited in the area in the late mid Cretaceous (Albian) in response to the final denudation and inundation of the London Platform.

The top Jurassic-Lower Cretaceous rocks of Norfolk are the most complete sequence of marine strata available in Britain for the study of the late Jurassic to mid Cretaceous interval. They crop out in a series of low escarpments running south from Hunstanton, via the eastern part of King's Lynn to Denver. Between Denver and the county boundary at the River Little Ouse, except for two small outliers which form the Fenland islands of Hilgay and Southery, the outcrop is concealed by Recent deposits. At its maximum, between King's Lynn and Gayton, the outcrop has a width of about 10 km (Fig. 1).

Late Jurassic - Mid Cretaceous

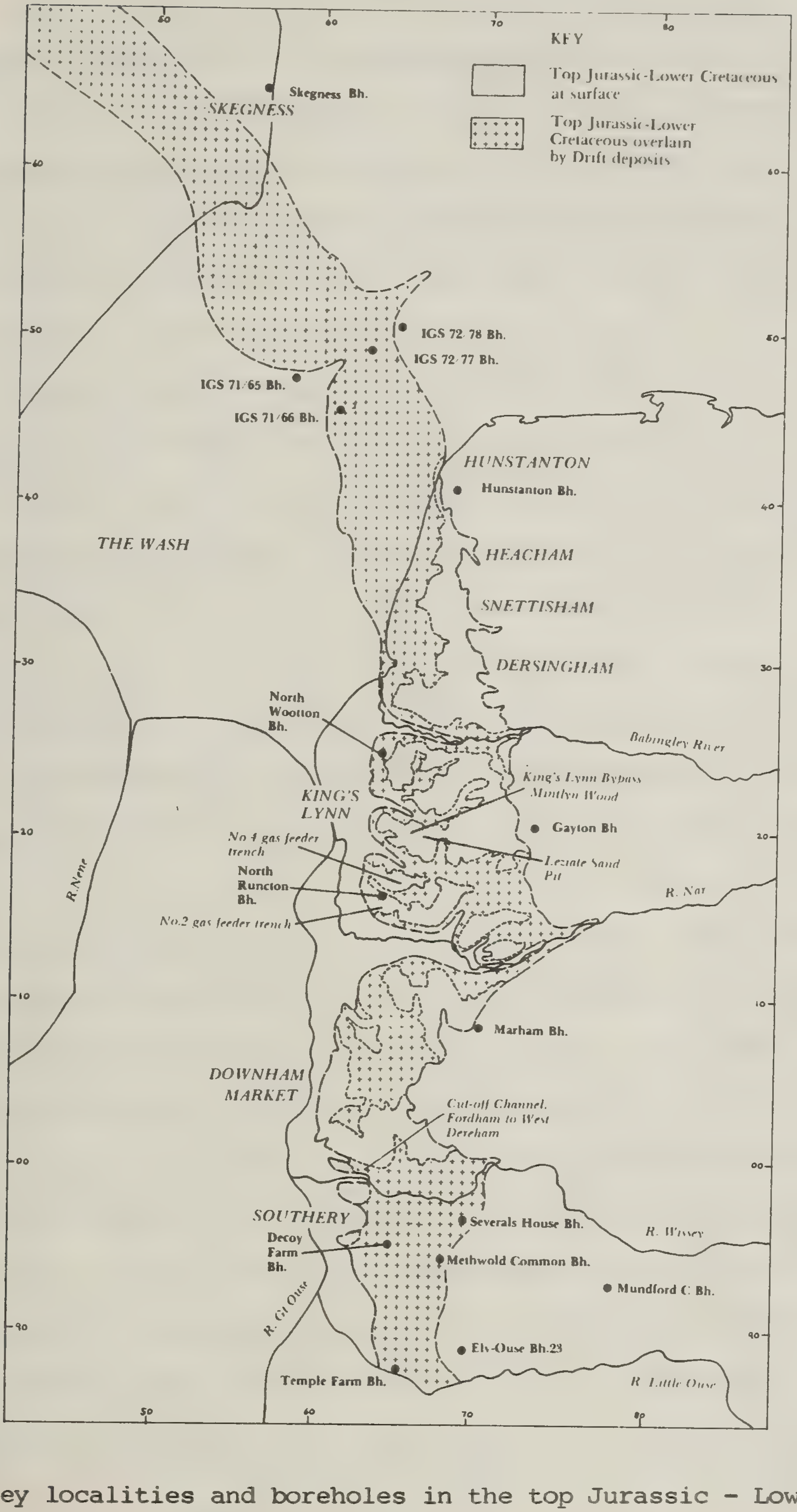

KEY
Top Jurassic-Lower Cretaceous at surface
Top Jurassic-Lower Cretaceous overlain by Drift deposits
50
60
70
80
90
00
10
20
30
40
Skegness Bh.
SKEGNESS
IGS 72/78 Bh.
IGS 72/77 Bh.
IGS 71/65 Bh.
IGS 71/66 Bh.
HUNSTANTON
Hunstanton Bh.
THE WASH
HEACHAM
SNETTISHAM
DERSINGHAM
North Wootton Bh.
Babingley River
King's Lynn Bypass Mintlyn Wood
KING'S LYNN
Gayton Bh
No 4 gas feeder trench
Leziate Sand Pit
North Runcton Bh.
R. Nar
No.2 gas feeder trench
R.Nene
Marham Bh.
DOWNHAM MARKET
Cut-off Channel, Fordham to West Dereham
SOUTHERY
Severals House Bh.
R. Wissey
Decoy Farm Bh.
Methwold Common Bh.
Mundford C Bh.
R. Gt Ouse
Ely-Ouse Bh.23
Temple Farm Bh.
R. Little Ouse

Fig. 1 Key localities and boreholes in the top Jurassic - Lower Cretaceous of Norfolk and The Wash

Much of the sequence is composed of alternations of loose sand and sandy clay that give rise to low, gently rounded features with few natural exposures. Between Hunstanton and the Babingley River these features are well displayed and provide considerable aid in geological surveying. South of the Babingley river the outcrop is overlain by extensive tracts of Quaternary deposits and features are less well developed.

As with many other parts of England, William Smith, in his pioneer geological maps of the counties, was the first to recognise the main divisions of the Jurassic and Cretaceous rocks of East Anglia. On his geological map of Norfolk (1819) he delineated the "Oaktree Clay" (Kimmeridge Clay) and the "Golt Brick Earth" (Gault) separated by "Sands" (Table 1).

Rose (1835-36, 1862), Teall (1875), Harmer (1877), Whitaker and Jukes-Browne (1899) and Lamplugh (in Whitaker and Jukes-Browne, 1899) contributed to the evolution of the stratigraphy and nomenclature of these rocks (Table 1).

Because of the paucity of exposure and the demise of the few brickpits that had yielded fossils, little new information was gained between the 1880s, the time of the Whitaker and Jukes-Browne survey, and 1961 when the first good sections became available through the lower part of the Sandringham Sands (in the Cut-Off Channel at West Dereham). Ammonites indicative of a late Jurassic to early Cretaceous age were obtained from the basal beds (Casey 1961a, 1963). Subsequent exposures in the cuttings for the King's Lynn Bypass (1964-5) and in gas-pipeline trenches in 1967-68 provided additional faunal and lithological details of the lower part of the Sandringham Sands and

Late Jurassic - Mid Cretaceous

Wm Smith 1819	Rose 1835, 1862	Teall 1875	Whitaker and Jukes-Browne 1899	Present Work	Modern Stages	
Chalk	Chalk	Chalk	Chalk	Chalk	Maastrichtian to Cenomanian	Upper Cretaceous
Golt Brick Earth	Red Chalk Gault	Red Chalk Gault	Red Chalk Gault	Red Chalk Gault	Albian	Lower Cretaceous
Sand beneath the Golt	'breccia'	Carstone	Carstone	Carstone		
			erosional gap	Sutterby Marl[1]	Aptian	
				Skegness Clay[1]		
				Roach	Barremian	
	Carstone	'clay'	Snettisham Clay	Snettisham Clay		
			Sandringham Sands	Dersingham Beds	Hauterivian	
	'loose white sand'	'white sands'		Sandringham Sands[2]	Valanginian to Volgian (pars)	
Oaktree Clay	Kimmeridge Clay	Kimmeridge Clay	Kimmeridge Clay	Kimmeridge Clay	Kimmeridgian	Upper Jurassic (pars)

[1] Submarine outcrops beneath The Wash only.

[2] See Table 2 for subdivisions of Sandringham Sands.

Table 1 Evolution of the nomenclature of the top Jurassic-Lower Cretaceous rocks of Norfolk

showed that this part of the formation underwent rapid lateral variation at outcrop.

The earlier sections showed the existing geological maps of the area to be inadequate and the Geological Survey therefore began a primary six-inch survey of the Norfolk Lower Cretaceous in 1965. Continuously-cored boreholes were drilled for stratigraphical purposes through the complete top Jurassic-Lower Cretaceous sequences at Skegness, Hunstanton, Gayton and Marham in 1970, to supplement the survey. The abrupt nature of the lateral lithological changes within the Lower Cretaceous of the area is such that the Skegness and Hunstanton boreholes could not be correlated in detail and two additional cored boreholes (IGS 72/77 and IGS 72/78) were subsequently drilled within The Wash by the drilling ship m.v. Whitethorn in 1972. These various sections and boreholes and the survey enabled new lithological (Casey and Gallois, 1973) and palaeontological (Casey, 1973) classifications to be devised for the Sandringham Sands.

The recognition by Casey (1961a) that the Jurassic-Cretaceous boundary, assumed by all previous workers except William Smith to be represented by the unconformity at the junction of the Kimmeridge Clay and Sandringham Sands, lay within a relatively complete, ammonite-bearing sequence, stimulated much discussion concerning the position of this boundary in other sequences in the Boreal province. William Smith had noted in the marginal comments on his 1819 map of Norfolk that the "Portland Rock" was occasionally found in the "Sand beneath the Golt", but the significance of this perceptive observation was overlooked for almost 150 years.

The stratigraphical results of the Geological Survey borehole at Hunstanton and the field survey suggested that the Snettisham Clay was not unconformably overlain by the Carstone throughout its outcrop (as had been supposed by Whitaker and Jukes-Browne, 1899) but that it was conformably overlain in the Hunstanton area by an equivalent of the Lincolnshire Roach (*sensu* Swinnerton, 1935). The presence of the Roach (Barremian in age) in Norfolk was subsequently confirmed by trenches dug on Hunstanton Beach. The Lower Cretaceous sequence in south-east Lincolnshire has long been thought, from the work of Swinnerton (1935), to be more complete than that in Norfolk because of the southerly overstep of the Carstone. In the Skegness Borehole the Roach is separated from the Carstone by two Aptian formations, the Skegness Clay and the Sutterby Marl. Thin representatives of both formations are also present in boreholes in the central part of The Wash but both have been removed by the unconformity at the base of the Carstone before the Norfolk coast is reached. The stratigraphical relationships of the top Jurassic-Lower Cretaceous formations between Skegness and West Dereham are shown diagrammatically in Fig. 2.

Because of its striking lithology and colour and its excellent exposure in the cliffs at Hunstanton the youngest Lower Cretaceous formation in the county, the Red Chalk, has attracted much attention in the past. It was first recorded by William Smith (1819) and its stratigraphical relationship as the lateral equivalent of Gault was appreciated as early as 1826 by Sedgwick. Southwards from Hunstanton the Red Chalk becomes progressively more argillaceous until, in the vicinity of Sandringham, it is partially replaced and, in the area south of the Bablingley River, wholly replaced by the Gault. Little has been written about this last-named formation in Norfolk and the Geological Survey memoir (Whitaker *et al*. 1893) describing south west Norfolk, and Jukes-Browne's review in the Cretaceous rocks of Britain

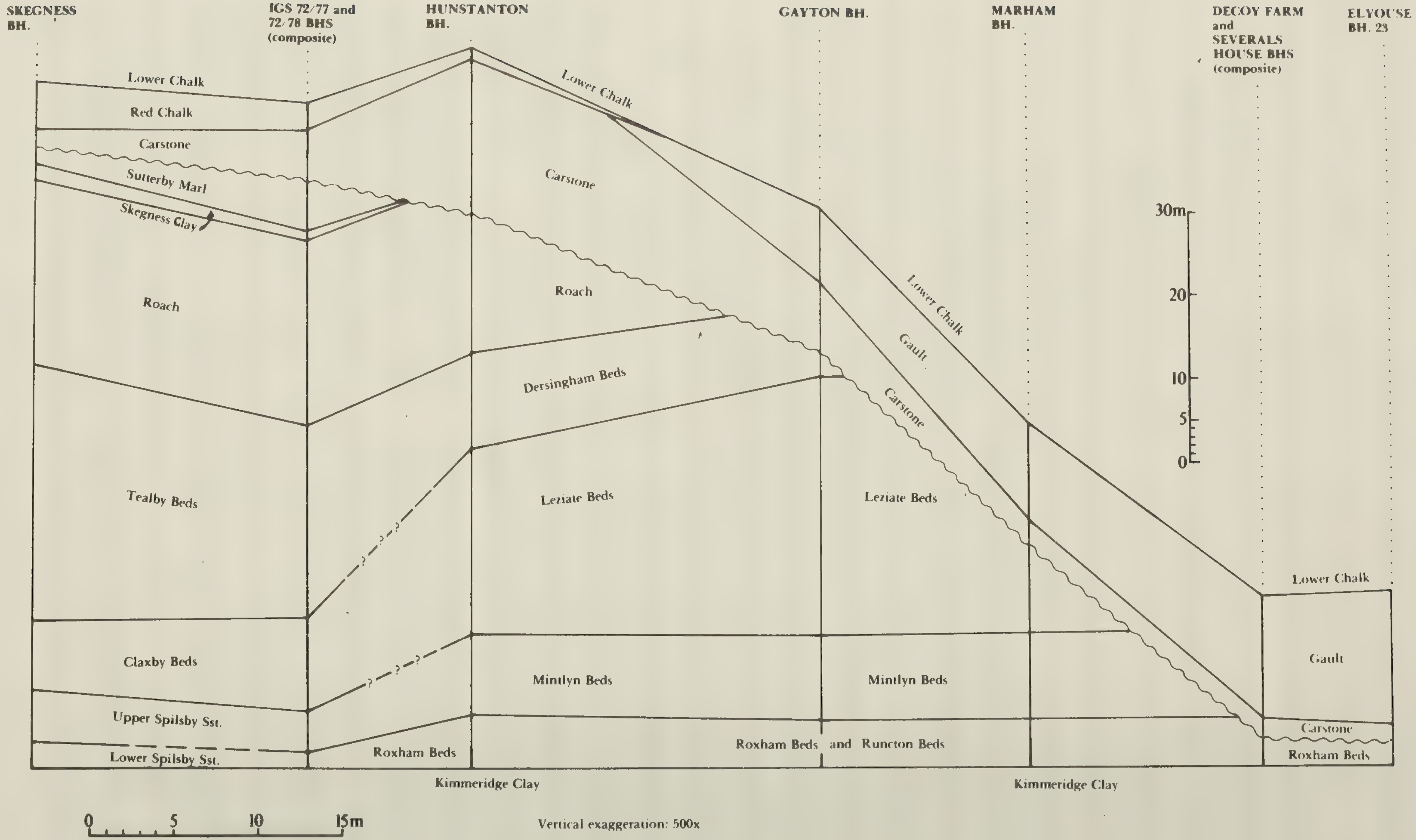

SKEGNESS BH.
IGS 72/77 and 72/78 BHS (composite)
HUNSTANTON BH.
GAYTON BH.
MARHAM BH.
DECOY FARM and SEVERALS HOUSE BHS (composite)
ELYOUSE BH. 23
Lower Chalk
Red Chalk
Carstone
Sutterby Marl
Skegness Clay
Roach
Tealby Beds
Claxby Beds
Upper Spilsby Sst.
Lower Spilsby Sst.
Roxham Beds
Lower Chalk
Carstone
Roach
Dersingham Beds
Leziate Beds
Mintlyn Beds
?
Lower Chalk
Gault
Carstone
Leziate Beds
Mintlyn Beds
Roxham Beds and Runcton Beds
Lower Chalk
Gault
Carstone
Roxham Beds
Kimmeridge Clay
Kimmeridge Clay
30m
20
10
5
0
0
5
10
15m
Vertical exaggeration: 500x

Figure 2 Stratigraphical relationships of the top Jurassic - Lower Cretaceous formations of Norfolk to one another. Top of Kimmeridge Clay taken as arbitrary datum. See Fig. 1 for borehole sites

(Vol. 1, 1900) remained the most comprehensive accounts until the recent description of the stratigraphy of the Gault in cored boreholes close to its outcrop (Gallois and Morter, 1982).

The stratigraphy of the late Jurassic to mid Cretaceous rocks of Norfolk has been reviewed by Larwood (1961) and their general stratigraphical relationships to Lower Cretaceous rocks elsewhere in England have been discussed by Boswell (1927), Kirkcaldy (1939; 1963) and Rawson et al. (1978). Their outcrop is covered by 1 to 50,000 Geological Sheet 129/145 (King's Lynn and The Wash; published in 1978), Sheet 159 (Wisbech; in preparation) and Sheet 173 (Ely; published in 1980).

SANDRINGHAM SANDS

The Sandringham Sands comprise a maximum of about 50m of predominantly arenaceous sediments which rise from the fringing marshes of The Wash near Heacham and form an almost continuous narrow outcrop from there to Downham Market (Fig. 1). Much of the outcrop is covered by Pleistocene deposits and, as the sediments are poorly consolidated, natural exposures are rare, small and generally deeply weathered.

At outcrop between Heacham and Ashwicken the Sandringham Sands are conformably overlain by the Dersingham Beds (Fig. 2). To the south of Ashwicken the Carstone rests directly on the Sandringham Sands and the unconformity at its base progressively cuts out the Sandringham Sands in a southerly direction. The Sandringham Sands have a relatively small subcrop. They were proved in deep hydrocarbon boreholes at Hunstanton, North Creake and South Creake and are probably present at Lexham. Sandringham Sands were absent from the Breckles, Great Ellingham and Rocklands boreholes. Traced north-westwards from their outcrop into The Wash the bulk of the Sandringham Sands become more clayey and pebbly. At most stratigraphical levels the lithologies that characterise the Norfolk outcrop cannot be recognised in Boreholes 72/77 and 72/78 (8.5 and 9.0 km from the Hunstanton respectively).

The Sandringham Sands can therefore be regarded as a mass of predominantly sandy sediment with a maximum proven area of distribution of about 12 km (from The Wash to the South Creake Borehole) by 55 km (from Hunstanton to the River Little Ouse). The extent of the subcrop north of Hunstanton beneath the North Sea is not known.

The original extent of the Sandringham Sands, even on the land area, can no longer be determined because of their later erosion by younger formations. Patches of sand, which may in part be correlatives of the Sandringham Sands, occur along the western margin of the London Platform as far south as Buckinghamshire. Only in The Wash, where the formation passes laterally into the more argillaceous Lincolnshire sequence, can the original depositional limit be determined with confidence.

The Sandringham Sands have been divided into four members, in asscending order the Roxham Beds, Runcton Beds, Mintlyn Beds and Leziate Beds (Table 2), on the basis of lithological characters that can be recognised in the field by means of exposures (mostly temporary excavations), soil fragments and topographical features. In drift-free areas, soil fragments of the more durable lithologies, notably phosphatic pebbles, ironstones and thin clays, are commonly exposed in drainage ditches. The interpretation of such data needs, however, to be treated with caution because the effects of late Pleistocene cryo-

Group	Formation	Zone (Casey, 1973; Casey and others, 1977)	Stage and Substage	System
	Dersingham Beds	not zoned	Hauterivian to Lower Barremian	CRETACEOUS (pars)
Sandringham Sands	Leziate Beds	not zoned	Valanginian	
	Mintlyn Beds	*Paratollia spp.*		
		Peregrinoceras albidum	Upper Ryazanian-Berriasian	
		Bojarkia stenomphala		
		Lynnia icenii		
		Hectoroceras kochi	Lower Ryazanian-Berriasian	
	remanié fauna in overlying nodule bed	*Praetollia (Runctonia) runctoni*		
	Runcton Beds	*Subcraspedites (Volgidiscus) lamplughi*	Upper Volgian	JURASSIC (pars)
	remanié fauna in overlying nodule bed	*Subcraspedites (Subcraspedites) preplicomphalus*		
	not recorded in Norfolk	*Subcraspedites (Swinnertonia) primitivus*		
	Roxham Beds	*Paracraspedites oppressus*	Middle Volgian	
	Kimmeridge Clay	*Pectinatites pectinatus*	Kimmeridgian	

●●● erosion surface and phosphatic nodule bed

Table 2 The subdivisions and zones of the Sandringham Sands

turbation and solifluction are widespread in Norfolk. Fortunately, the geological structure is extremely simple; dips are mostly eastwards to northeastwards and no faulting has been recorded, with the result that the features can usually be interpreted with confidence.

The rich ammonite faunas obtained from the Sandringham Sands in Norfolk, with supplementary material obtained from the Spilsby Sandstone of Lincolnshire, enabled Casey (1973) to establish the first British zonal scheme for the beds at this (Volgian and Ryazanian) stratigraphical level. The zonation and nomenclature of the Sandringham Sands is summarised in Table 2. The availability of unweathered material from marine, fossiliferous sands that straddle the Jurassic-Cretaceous boundary prompted additional palaeontological studies. Ager (1971) has described the brachiopods, Creber (1972) the gymnospermous wood, Kelly (1977, 1984) the bivalves and Pinckney (1978) the belemnites of the lower part of the Sandringham Sands.

Earlier work on the Sandringham Sands includes Pringle's (1920, 1923) descriptions of the formation in boreholes in west and southwest Norfolk, Kent's (1947) description of the North Creake Borehole, Rastall's (1919, 1925) and Boswell's (1927) descriptions of the heavy mineral assemblages, and Schwarzacher's (1953) description of the sedimentary features.

Roxham Beds

The basal member of the Sandringham Sands consists of 3m to 6m of poorly consolidated grey and yellowish-green, locally glauconitic sands with disseminated pyrite and, at some levels, pyritic nodules (Fig. 3). They have been mapped from their most northern occurrence on the banks of the Babingley River to their disappearance beneath

Methwold Fens, near Southery. Temporary sections have shown the member to remain lithologically uniform at outcrop, and this uniformity has been confirmed in the subcrop by boreholes at Hunstanton, North Wootton, Gayton, Marham, Mundford, Southery and Little Ouse. When traced north-westwards from the Babingley River beneath The Wash, the thickness of the Roxham Beds is reduced by erosion at the base of the overlying Mintlyn Beds. The Roxham Beds continue into Lincolnshire as the lower part of the Spilsby Sandstone.

At the base of the member the junction with the Kimmeridge Clay is marked by an erosion surface overlain by up to 1m of densely calcite-cemented, fine-grained, grey sandstone, crowded in its lower part with pebbles of black chert (lydite) and black phosphate. Many of the latter are water-worn moulds of pavlovid ammonites and myid bivalves derived from the Kimmeridge Clay. Vein quartz and other pebbles occur less frequently. The basal sandstone is intensely bioturbated throughout with *Ophiomorpha* and other burrows common, and with *Ophiomorpha* and *Skolithos* burrows filled with sand penetrating several tens of centimetres into the underlying Kimmeridge Clay.

The most prolific source of indigenous fossils from the Roxham Beds has been this basal sandstone. Pyritized fossils occur sparingly in the overlying loose sands. At outcrop above the water table most of these fossils are destroyed by dissolution and/or oxidation. Where unweathered, the basal sandstone contains abundant ammonites, mostly *Paracraspedites* spp., the belemnite *Acroteuthis*, the large terebratulid brachipod *Rouillieria ovoides* (J. Sowerby) and numerous bivalves including common *Entolium*, *Oxytoma*, *Modiolus*, *Myophorella* myids and oysters (see Kelly, 1984). The sands contain poorly preserved *Paracraspedites* and bivalves. Many of the fossils known

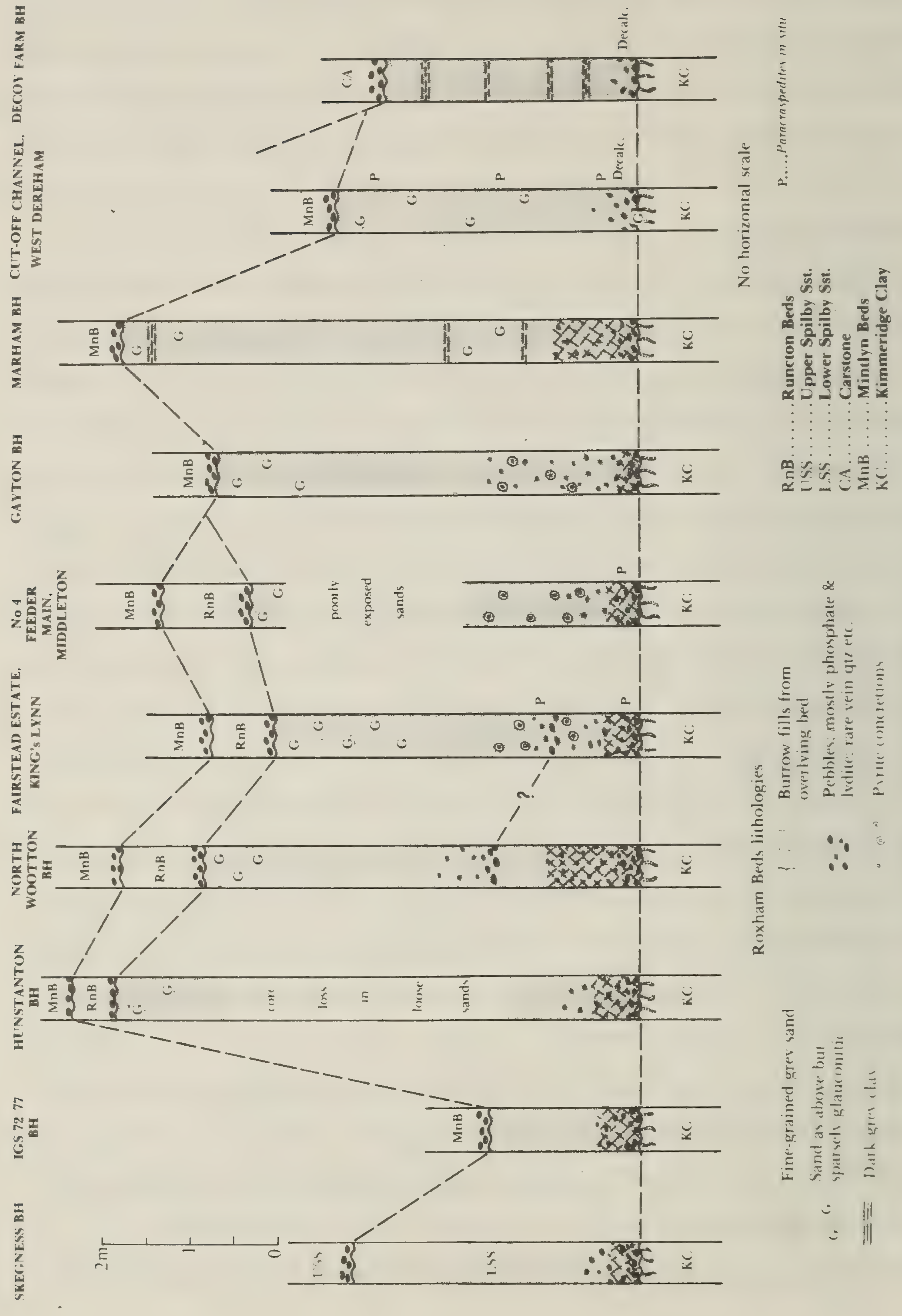

SKEGNESS BH
IGS 72 77 BH
HUNSTANTON BH
NORTH WOOTTON BH
FAIRSTEAD ESTATE, KING's LYNN
No 4 FEEDER MAIN, MIDDLETON
GAYTON BH
MARHAM BH
CUT-OFF CHANNEL, WEST DEREHAM
DECOY FARM BH
2m
1
0
USS
LSS
MnB
RnB
G
CA
KC
P
Decalc.
?
core loss in loose sands
poorly exposed sands
No horizontal scale
P.....Paracraspedites in situ
RnB.......Runcton Beds
USS.......Upper Spilby Sst.
LSS.......Lower Spilby Sst.
CA.........Carstone
MnB.......Mintlyn Beds
KC.........Kimmeridge Clay
Roxham Beds lithologies
Fine-grained grey sand
Sand as above but sparsely glauconitic
Dark grey clay
Burrow fills from overlying bed
Pebbles, mostly phosphate & lydite; rare vein qtz etc.
Pyrite concretions
Major erosion surface

Figure 3 Correlations between the Roxham Beds and Runcton Beds sequences in Norfolk

from the basal bed have actually come from erratic boulders of it preserved in the Chalky-Jurassic till that covers much of the Sandringham Sands outcrop.

Runcton Beds

The Runcton Beds consist of up to 1.5m of green, clayey, highly glauconitic sands with phosphatic nodule/pebble beds at several levels. They are intensely bioturbated throughout and no other sedimentary structure has been recorded in them either at outcrop or in boreholes. The base of the member rests unconformably and with marked colour contrast on a burrowed surface of Roxham Beds. The Runcton Beds have been mapped out almost continuously between North Wootton and Downham Market. They attain their maximum thickness, estimated from the geological survey, at outcrop in the North Runcton area. Temporary sections show them to consist of dark green, glauconitic, clayey sand with bivalves and ammonites in clay-cast and phosphatic preservation.

The member is highly condensed and non-sequences, separated by phosphatic pebble beds, bound it and occur within it in such a complex manner that the member is laterally very variable (Fig. 3).

The fauna of the Runcton Beds is sparse. Derived Subcraspedites (Subcraspedites) indicative of the former presence of the preplicomphalus Zone, occur in the basal pebble bed of the member at North Runcton and Subcraspedites (Volgidiscus) lamplughi Spath, the zonal index of the lamplughi Zone, the youngest Jurassic zone recognised to date in Britain, is present in a fragile soft brown phosphatic preservation (clearly indigenous). Casts of small indigenous bivalves also occur, but neither they, nor the ammonites, survive weathering at outcrop.

Mintlyn Beds

The Mintlyn Beds consist of grey, greyish green and green glauconitic sands and clayey sands with thin beds and lines of doggers of clay ironstone (siderite mudstone) and thin (mostly 15 cm) beds of green glauconitic clay. Erosion surfaces marked by phosphatic pebble beds occur at two or more levels in the lower part of the member. The high iron content and low permeability of the Mintlyn Beds cause them to weather to poorly drained, dirty orange-brown sand with much secondary limonite (commonly in the form of iron-pan).

In the few large exposures recorded in the Mintlyn Beds, the ironstone bands and clay seams appear to be even and parallel-bedded over long distances. Small-scale sedimentary structures are rare at outcrop because of the deep weathering, but in borehole cores bioturbation, planar lamination and rarer cross-lamination are picked out by clay wisps and concentrations of glauconite, shell debris, carbonaceous sand and clean white sand.

Indeterminate burrow mottling occurs throughout the member, with *Chondrites* and *Rhizocorallium* common at several levels. Minor erosion surfaces with cf. *Skolithos* and other burrows commonly mark the junctions of two lithologies, and several of the ironstones are partially phosphatized to form hardgrounds, each with a burrowed and bored upper surface that carries a concentration of shells and, in a few instances, phosphatic pebbles. Body fossils are rare except in the ironstones and a few pyritic concretions, and as casts in some of the thicker clay seams. Plant scraps and bits of coalified wood are common throughout.

The Mintlyn Beds crop out almost continuously between Wolferton and West Dereham, mostly on low ground. In most areas, the higher part of the member is largely covered by loose sandy wash derived from the overlying Leziate Beds. Only on the interfluves at the widest part of their outcrop, between the Babingley River and the River Nar, can they be readily studied. The member takes its name from that area, from the former parish of Mintlyn near King's Lynn, where much of the sequence was formerly exposed in the Mintlyn Wood cutting of the King's Lynn bypass.

Eastwards from their outcrop the Mintlyn Beds are present in the same lithologies in the Hunstanton, Gayton and Marham boreholes. Their original depositional thickness appears to have been somewhat variable in its known area of preservation. They thin slightly northwards and eastwards from an estimated thickness of about 20m at King's Lynn to 11.4m in the Hunstanton Borehole, 12.9m in the Gayton Borehole and 14.0m in the Marham Borehole. At outcrop, the progressive southerly overstep of the Carstone across the Sandringham Sands brings the Carstone to rest on the Mintlyn Beds at Ryston Park, Denver, and then cuts them between there and Southery. Only the lowest 6.5m of the member is present in the Cut-Off Channel at West Dereham. A thin (5.2m) representative of it, overlain by Claxby Beds, was recorded in the central part of The Wash in Borehole 72/77.

Throughout their outcrop, the Mintlyn Beds rest unconformably on the Runcton Beds or, between the Cut-Off Channel and Hilgay, on the Roxham Beds. In most sections the erosive nature of the basal phosphatic pebble bed of the Mintlyn Beds is clearly demonstrated by its irregular, commonly channelled, contact with the underlying beds. Derived Subcraspedites are common as phosphatic pebbles in this bed. Phosphatic nodules and slabs of fossiliferous ironstone are common as spoil thrown out from the deeper excavations and drains throughout the outcrop.

In the North Runcton and King's Lynn areas the basal nodule bed yielded fragments of phosphatized ammonites that Casey (1973, p.242) considered to have affinities with both the Jurassic (Upper Volgian) genus *Subcraspedites* (*Volgidiscus*) and the Cretaceous (Lower Ryazanian) genus *Hectoroceras*. He has named these (Casey *et al*. 1977, p.16) *Praetollia* (*Runctonia*) and has suggested, on the basis of comparison with the late Jurassic to early Cretaceous faunas of NW Europe, the Russian Platform, the Subarctic Urals, Northern Siberia and Greenland, that they are the oldest Cretaceous fauna yet recognised in Britain. The base of the Mintlyn Beds in Norfolk (and its equivalent in Lincolnshire - the mid-Spilsby nodule bed) has therefore been taken to mark the Jurassic-Cretaceous boundary in eastern England (Casey, 1973).

The fossiliferous ironstones in the Mintlyn Wood cutting yielded a rich ammonite and bivalve fauna. The ammonites include, in ascending order, species of *Praetollia* (*Runctonia*), *Hectoroceras* and *Borealites, Lynnia* (formerly *Surites* (*Lynnia*), *Bojarkia* (formerly *Surites* (*Bojarkia*) and *Peregrinoceras* indicative of the *kochi, icenii, stenomphalus* and *albidum* zones of the Ryazanian (Casey, 1973; Casey *et al*. 1977).

The bivalves have been identified by Kelly (1984); they include species of *Anisocardia, Camptonectes, Corbula, Cucullaea* (*Dicranodonta*), *Girardotia, Myophorella, Neocrassina* (*Lyapinella*), *Neocrassina* (*Pressastarte*), *Nicaniella, Pinna, Pleuromya, Protocardia, Thracia* and ostreids. None of this diverse bivalve fauna appears to be diagnostic of any particular bed within the Mintlyn Beds. Indeterminate gastropods and wood fragments are also present.

The highest part of the Mintlyn Beds is poorly exposed and has not yielded any fauna at outcrop. A specimen of Paratollia, indicative of a Valanginian age, was recorded in the upper part of the formation in Borehole 72/77 in the Wash (Morter in Gallois and Morter, 1979, p.25), thereby suggesting that the Ryazanian-Valanginian boundary falls within the top part of the Mintlyn Beds in that area.

The age of the preserved Mintlyn Beds varies throughout the length of their outcrop. At West Dereham ironstones within the formation are rich in Hectoroceras and include over 25 species of bivalve, lignite logs up to 1m long and bones and teeth of large marine reptiles (Casey, 1971). These beds were assigned by Casey (1973) to the Hectoroceras kochi Zone. When traced northwards this lower part of the Mintlyn Beds (the Hectoroceras Beds) becomes attenuated due to erosion at the base of the overlying bed. At North Runcton (4m) and Mintlyn Wood (1m) the Hectoroceras Beds are overlain with minor unconformity by sands with Lynnia. As yet, the Hectoroceras Beds are unknown in England outside Norfolk. However, Hectoroceras occurs widely in the Boreal provice and has been recorded from East Greenland, Western Siberia, the Subarctic Urals, Canada, and the Central Graben in the North Sea.

Leziate Beds

The Leziate Beds consist of loose, fine-grained, cross-bedded quartz sands, yellow, green, orange-brown or red in places, but mostly clean grey or white, with subordinate bands of silt and clay. Locally the sands are sufficiently lithified to form a friable sandrock. Pyrite nodules are common throughout the member, but above the water-table these become oxidised to form limonitic concretions, geodes or merely ferruginous stains. Glauconite is abundant in some areas and at some stratigraphical levels in the Leziate Beds, but is rare in others. Phosphatic nodules or other signs of erosion and condensed deposition appear to be absent. At outcrop, the clay and ferromagnesian minerals are commonly weathered and leached to give a clean white sand with a little patchy yellow staining.

The sands rise from beneath The Wash at Heacham and can be traced from there southwards to Denver. From Heacham to King's Lynn they crop out on the face of a steep feature that is capped by the basal ferruginous sandstones of the overlying Dersingham Beds. South of King's Lynn they form a more subdued feature capped by Carstone. Much of the heathland of west Norfolk that is regarded as typical Sandringham Sands scenery, including Dersingham Heath, Sandringham Warren, Roydon Common, Leziate Heath and Shouldham Warren, is underlain by the free-draining Leziate Beds, basal Dersingham Beds and, at the foot of the Leziate Beds feature, by thick sandy wash derived from the Leziate Beds. The member underlies much of west Norfolk and was proved in the Hunstanton and Gayton boreholes. When traced north-westwards into The Wash the sands pass laterally into argillaceous Claxby Beds. The Leziate Beds are 20.4m thick at Hunstanton but thicken steadily southwards from there to an estimated maximum of about 30m in the Leziate-Middleton area. The are represented in Borehole 72/77 by only 2.5m of fine-grained sand in the top part of the Claxby Beds sequence.

The absence of the marker beds within the Leziate Beds makes it impossible to determine whether the variation in their thickness is due to overstep by the Dersingham Beds or to original differences in the depositional thickness. Their rapid attenuation beneath The Wash strongly suggests an original depositional variation. Southwards from Middleton, the Carstone rests on the Leziate Beds, and between there and their disappearance at Ryston Hall, Denver, they are progressively cut out in a southerly direction.

The type section of the member is the huge complex of pits dug for glass and foundry sands at Leziate Heath [675 193], about 5 km east of King's Lynn. The junction with the underlying Mintlyn Beds has been well exposed from time to time in the most westerly part [665 195] of the pits. There, and in the Hunstanton, Gayton and Marham boreholes, the base of the Leziate Beds has been taken at the top of a thin bed of dark green glauconitic clay; the overlying lithologically uniform sands differ from the Mintlyn Beds in that they contain rare clay seams but no clay ironstone. This junction effectively marks the lower limit of the economically useful sands.

The sand-pits at Leziate are the most extensive workings of their kind in Britain. They were probably begun in the early part of the 19th century as small pits for glass sand. In recent years they have been worked by British Industrial Sands Ltd for glass and foundry moulding sands and they now extend over about 2 km square. The full thickness of the Leziate Beds has been worked in the pits. The sands are mostly clean, well sorted and fine-grained with patchy irregular ferruginous staining present above the water-table and the iron-bearing minerals glauconite and pyrite present below. The degree of staining, and hence the iron content, varies considerably over short distances, but the bulk of the sand above the water-table is white, grey or pale yellow and relatively free from iron due to leaching by acidic meteoric water.

In the past (mostly in the 19th century), the Leziate Beds were worked for glass sand in the Snettisham, Dersingham, Roydon, Castle Rising, Blackborough, Shouldham and Downham Market areas.

Bioturbation in the form of indeterminate mottling is common at all levels in the Leziate Beds in boreholes. Vertical or sub-vertical tubes cf. Skolithos, commonly cemented by pyrite or limonite, are very common; poorly preserved Rhizocorallium is also present, but rare. Possible burrows or casts of bits of rotted wood, lined with a carbonaceous film, are common at several levels, especially in the lower part of the member. Tiny, hollow pyritized tubes penetrate many of the clay bands; these are presumed to be burrows rather than the traces of rootlets. Plant stems and bits of wood, much of it cemented into pyritized masses, are common in the lower part of the member where they appear to have formed waterlogged mats on the sea bed. Parallel lamination and cross-lamination, picked out by sand or glauconite grains in thin clay beds or by clay laminae within the sands, are common in the lower part of the Leziate Beds in boreholes.

Although cross-bedding and other sedimentary features are present in even the smallest exposures of Leziate Beds, the sections are so widely spaced that they can only be qualitatively assessed. Lithological variations are also present whose significance, whether regional or local, is impossible to assess. Despite these limitations, the following generalisations can be made:

(i) the sands are predominantly fine-grained throughout their outcrop but bands of medium-grained sand are more common in more northerly exposures and a few thin bands of coarse-grained sand, including tiny pebbles of ironstone and mudstone, are present in the Hunstanton Borehole.

(ii) they are finely micaceous at several levels at Hunstanton, and possibly at Snettisham, but become glauconitic south of Snettisham with the overall glauconite content, both as grains and as wisps and thin seams of glauconitic clay, increasing southwards. In the southern part of the district, at Blackborough, some thin bands of sand contain more than 40% glauconite

(iii) thin seams, wisps and clay drapes of grey carbonaceous clay occur throughout the outcrop, but glauconitic clay is restricted to its southern part

(iv) the commonest sedimentary feature is slightly curved planar cross-bedding. This occurs at all but the highest stratigraphical levels, mostly in units 0.15m to 0.45m thick whose boundaries are parallel over larger distances than those visible in the exposures. Current reversals ('herringbone bedding') are common in many of these units. Even-parallel bedded units of similar thickness are also common. Planar cross-bedded units up to 1.5m thick were recorded at Leziate Sand Pit, and in a probable broad channel at Snettisham Common. Small channel-fill structures occur in several of the boreholes

(v) single lines of ripples are present, but rare, at several stratigraphical levels at most localities and are present, usually accompanied by clay drapes, in the highest 0.5m of the Leziate Beds at most of the localities where the member is overlain by the Dersingham Beds.

Schwartzacher (1953), in a comparative study of grain size and cross-bedding in the Sandringham Sands of Norfolk and the Woburn Sands of Cambridgeshire, measured cross-bedding dips at Snettisham Common, Dersingham, Wolferton, North Wootton, Leziate, Blackborough End and South Runcton. He noted a preponderance of easterly dips that led him to conclude that the sands had been derived from a north-south coastline that had lain between Lincolnshire and Norfolk. 'Herringbone' bedding was noted to be a minor feature at most localities; it accounted for more than 5% of the cross-bedding only at Snettisham Common, North Wootton, Leziate, Blackborough End and South Runcton.

An unusual feature of the Leziate Beds outcrop in the Castle Rising area, noted originally by Rose (1835), is the common occurrence of blocks of hard, pure quartzite up to 1m across. Their field relationships and textures indicate that they are a form of silcrete, probably of Pleistocene age.

Although well exposed in comparison with the other Lower Cretaceous formations in Norfolk, the Leziate Beds are palaeontologically the least rewarding part of the sequence. No body fossil has yet been recorded in situ in the sands but, in unweathered sections, pyritic concretions have yielded bits of coalified wood and, more rarely, poorly preserved bivalves and rare unidentifiable ammonite 'ghosts'. None of the determinable fossils is stratigraphically diagnostic. An ammonite body chamber found in an old sand pit at Roydon Common [678 220], and believed to have been derived from the Leziate Beds, was identified by Casey (in Casey and Gallois, 1973) as a ?*Polyptychites*. This supports the presumed Valanginian age of the formation.

DERSINGHAM BEDS

The Dersingham Beds comprise a laterally variable, rhythmic sequence of thinly interbedded, fine-grained sands, ferruginous sandstones, silts and clays. The formation has an almost continuous, largely drift-free outcrop, between Heacham and the Babingley River. Southwards from there it crops out, mostly as a narrow strip from beneath extensive drift deposits, as outliers at Rising Lodge, Brow of the Hill and East Winch with the main outcrop on low ground between Roydon and Ashwicken. The Dersingham Beds are cut out by the southerly overstep of the Carstone in the vicinity of East Winch. The extent of their subcrop is poorly known. The formation was proved in the Gayton and Hunstanton boreholes and might be expected to occur beneath much of north-west Norfolk.

At outcrop, the formation undergoes a broad lithological change, in addition to minor local variations, from predominantly arenaceous in the south to a mixture of arenaceous and argillaceous in the north. Between the most northerly outcrop (at Heacham) and the Hunstanton Borehole, the formation undergoes a rapid change to become predominantly argillaceous. The Dersingham Beds pass into the Tealby Beds beneath the Norfolk side of The Wash.

The formation takes its name from the Dersingham area where the harder bands within a predominantly sandy sequence about 16m thick give rise to a series of drift-free terrace-like features that, despite the paucity of exposure, enable the broad lithological sequence to be demonstrated. Throughout the Dersingham Beds outcrop the highest bed of the formation is a thin (1.5m in the south thickening to 6m in the north) but laterally persistent bed of clay that Whitaker and Jukes-Browne (1899, pp.6 and 9) termed the Snettisham Beds [Clay]. The stratigraphical relationship of this bed to the remainder of the Dersingham Beds is still not entirely clear.

In the Hunstanton Borehole the Dersingham Beds consist of 11.6m of clays and silts that form a complex rhythmic sequence. Many of the rhythms have erosional bases that bound beds of sparsely fossiliferous strata, and few detailed correlations can be made with the succession at outcrop. The Dersingham Beds are not exposed between the borehole and Heacham, and are poorly exposed between the latter locality and the type area. The lower part of the clayey sequence in the borehole appears to pass southwards in the Heacham-Snettisham area into a complex sequence of thinly interbedded sands, silts and clays. The Hunstanton sequence passes beneath The Wash into the even more argillaceous Tealby Beds. Both sequences are made up of fining-upward rhythms (Fig. 4). The Snettisham Clay appears to be the correlative of one or possibly two rhythms in the upper part of the Hunstanton Borehole sequence; each of the lithologies in the generalised Hunstanton rhythm is present in Snettisham Clay spoil in the Heacham to Snettisham area, but the exposures are now too poor for their sequences to be determined. Even with good exposure, it would be difficult to make correlations in this type of sparsely fossiliferous sequence that contains numerous erosion surfaces.

The base of the Dersingham Beds rests with sharp lithological contrast on the loose clean white sands of the Leziate Beds. The basal bed is usually a few centimetres of clay overlain by about 3 to 5m of fine-grained ferruginous sandstone. The contrast in permeability and hardness between the Leziate Beds and the basal Dersingham Beds gives rise to a weak spring line and one of the most prominent features in Norfolk.

The basal ferruginous sandstones have been well exposed in the past in quarries at Dersingham (Rose, 1862, p.31), Sandringham Warren and Wolferton (Lamplugh *in* Whitaker and Jukes-Browne, 1899, p.17), and the junction with the Leziate Beds has been exposed in sand pits at

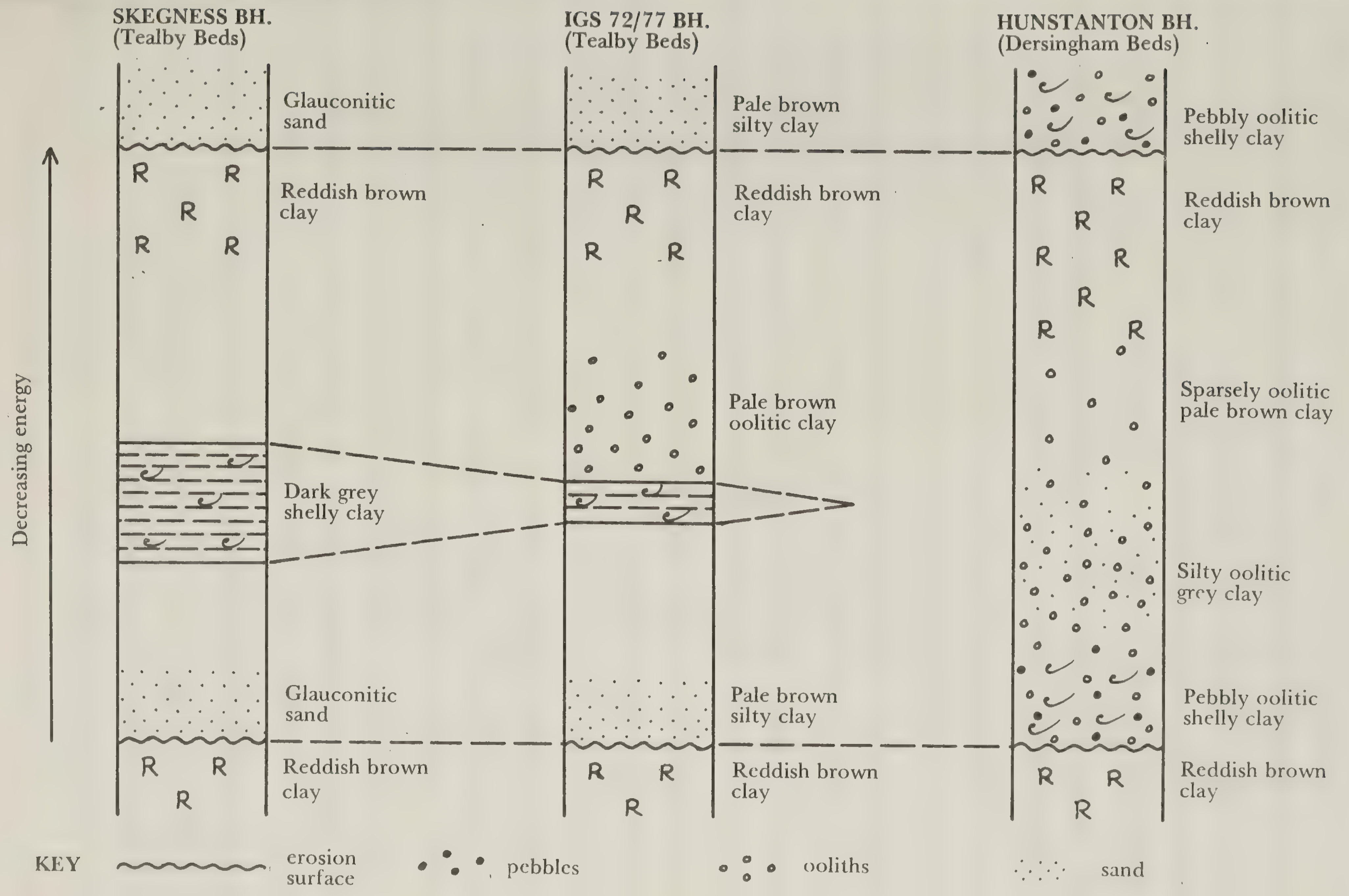

SKEGNESS BH.
(Tealby Beds)
IGS 72/77 BH.
(Tealby Beds)
HUNSTANTON BH.
(Dersingham Beds)
Glauconitic sand
Reddish brown clay
Dark grey shelly clay
Glauconitic sand
Reddish brown clay
Pale brown silty clay
Reddish brown clay
Pale brown oolitic clay
Pale brown silty clay
Reddish brown clay
Pebbly oolitic shelly clay
Reddish brown clay
Sparsely oolitic pale brown clay
Silty oolitic grey clay
Pebbly oolitic shelly clay
Reddish brown clay
Decreasing energy
R
KEY
erosion surface
pebbles
ooliths
sand

Figure 4 Correlation of generalized rhythms in the early Barremian sediments of The Wash area (not to scale)

Roydon Common, Dersingham and Snettisham. The middle part of the formation has never been well exposed. The features in drift-free areas such as Sandringham Park and Lodge Hill, Snettisham suggest that it includes several relatively thick clay seams; small, degraded brickpits are present in both areas.

SNETTISHAM CLAY

The Snettisham Clay can be traced almost continuously at outcrop from Heacham to Ashwicken. It was well exposed in Victorian times when it was dug for brickmaking at Heacham, Snettisham, Ingoldisthorpe, Dersingham and Bawsey. Jackson (1911, p.63) recorded the full thickness of the Snettisham Clay at Heacham Brickworks [678 364] as 9m of greyish brown clay with a line of fossiliferous clay ironstones about 3m from the top, and with ironstone concretions scattered throughout. Loose spoil in the modern pit suggests that the clays rested on white sands, the junction being marked by a band of ferruginously cemented sandstone with small quartz and other pebbles including angular clay clasts. Evidence of a break in sedimentation at the base of the Snettisham Clay is also present at other localities and it is probable that it rests with minor unconformity on the underlying beds throughout its outcrop. In the Leziate, Ashwicken and East Winch areas the Snettisham Clay appears to cut out the lower and middle parts of the Dersingham Beds and rests on the Leziate Beds.

Sedimentary features, other than lamination picked out by partings of sand, are rare in the Snettisham Clay at outcrop. In the Gayton Borehole, bioturbation in the form of tracks, trails, vertical and sub-horizontal tube-shaped burrows and large poorly defined burrows, are common at several levels.

Late Jurassic - Mid Cretaceous

Many of the Dersingham Beds lithologies are sparsely fossiliferous, largely because of their unsuitability for preservation. The two notable exceptions are the ferruginous sandstones at the base of the formation and the clay ironstone nodules in the Snettisham Clay, both of which have given rise to extensive museum collections. The three exposures in the basal sandstones, at Wolferton [662 287], Sandringham Warren [669 276] and Roydon Common [675 222], that were listed by Whitaker and Jukes-Browne (1899, p.27) as fossiliferous, are still open and they, together with a small number of additional exposures in the same area, have yielded a relatively rich fauna. This is dominated by bivalves (24 species), but includes common plant fragments, trace fossils, serpulids and gastropods and rare ammonites and echinoids. The ammonites include species of *Endemoceras* that indicate an early Hauterivian age.

The former brickworks in the Snettisham Clay at Heacham, Snettisham and Ingoldisthorpe yielded a rich bivalve fauna, common gastropods, ammonites, plant fragments and serpulids, and rare brachiopods, belemnites, crinoids and fish debris. Many of the ammonites are well preserved as uncrushed red or brown ironstone casts and they were much sought after when the pits were in work. Many of the finer specimens are now in museum collections. They all belong to crioceratid genera and were shown by Spath (1924) to be indicative of a Barremian age.

The sections are all now degraded and the published descriptions of several of them are either incomplete or in disagreement with one another. The provenance of much of the fauna can no longer be demonstrated, but re-examination of museum collections by Mr A.A. Morter strongly suggests that the bulk of it belongs to one or other of two assemblages of differing ages. Contemporary descriptions of the brickpits suggest that these assemblages came from two separate horizons, one close to the base of the Snettisham Clay and one in its upper part. The older fauna is by far the more varied and includes plants, annelids, brachiopods (2 species), bivalves (22 species), gastropods (7 species), crioceratid ammonites including *Acrioceras* sp., species of the belemnites *Aulacoteuthis* and *Praeoxyteuthis* and fish vertebrae, all preserved as nests in large rusty brown clay-ironstone concretions or in ferruginous oolitic clays. The ammonites and belemnites suggest correlation with the early Barremian zone of *Crioceratites* (*Hoplocrioceras*) *fissicostatum* (Morter, pers. comm.). The younger fauna is more limited and consists of species of *Crioceratites* (*Hoplocrioceras*) and *C.* (*Paracrioceras*) and a few bivalves and gastropods, beautifully preserved in buff, red or purplish red clay ironstone. The ammonites are indicative of the mid-Barremian zone of *Crioceratites* (*Paracrioceras*) *elegans* (Morter, pers. comm.)

At Hunstanton, the Snettisham Clay is conformably overlain by the Roach. Everywhere south of there it is unconformably overlain by the Carstone, and is overstepped by that formation near East Winch. At outcrop between Snettisham and Leziate, the Snettisham Clay and Carstone appear to have a concordant relationship in which their basal unconformities are almost parallel to one another. Correlation of the more important Dersingham Beds sequences in the district with one another is shown in Figure 5.

ROACH

The presence of clay beneath the Carstone outcrop on Hunstanton beach appears to have been first recorded by Rose (1835) who presumed

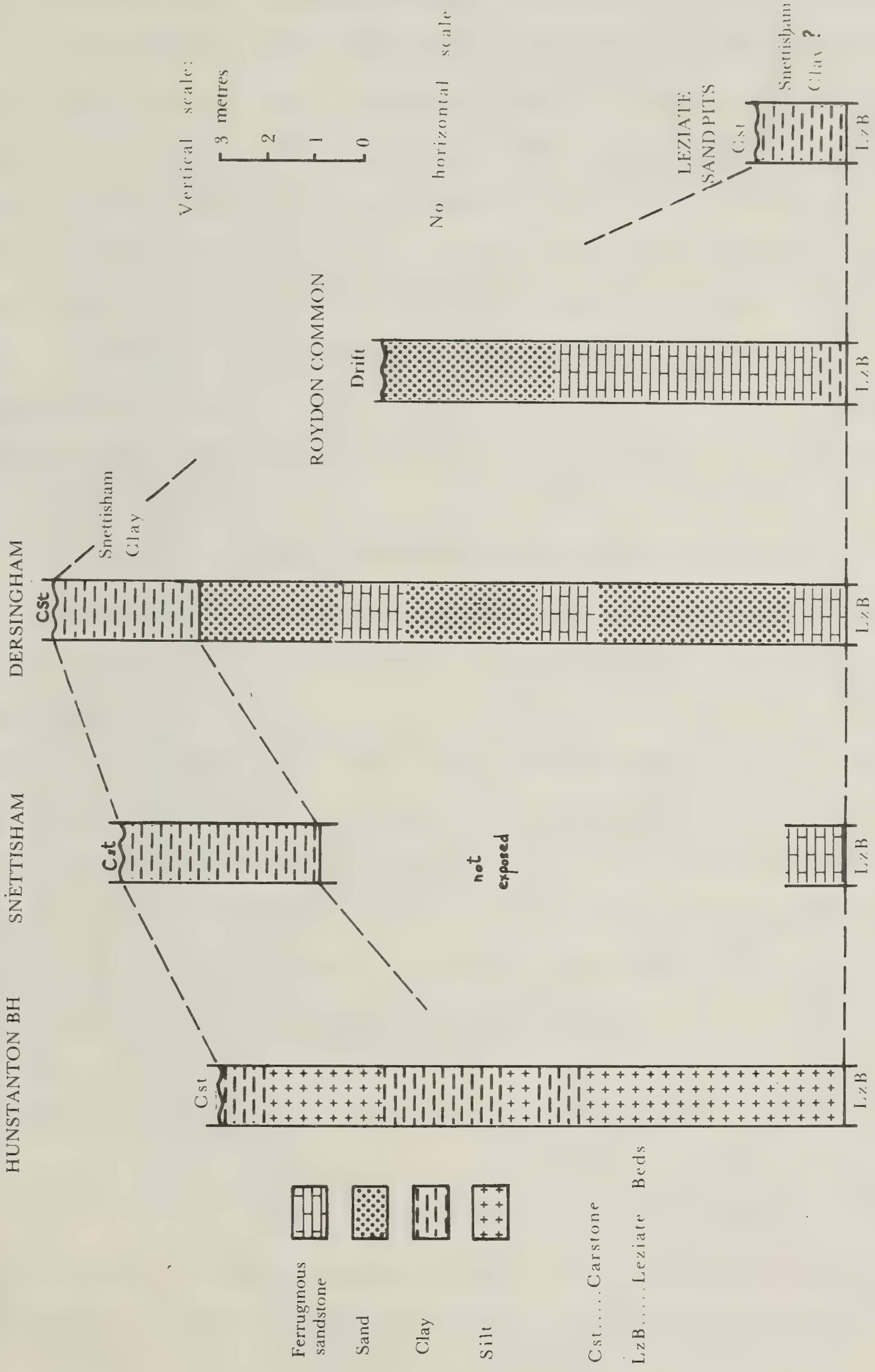
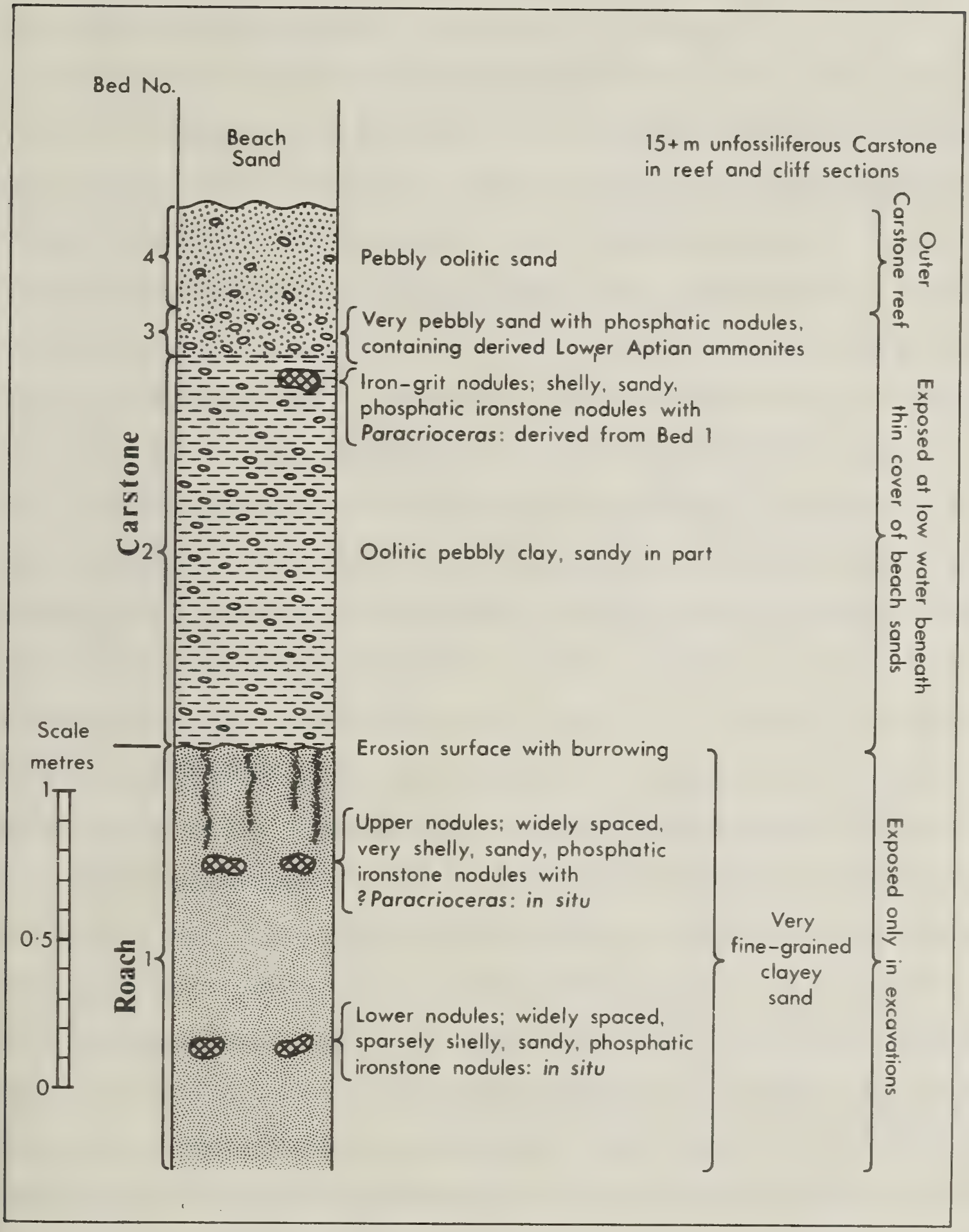

HUNSTANTON BH
SNETTISHAM
DERSINGHAM
ROYDON COMMON
LEZIATE SANDPITS
Cst
LzB
Snettisham Clay
Snettisham Clay ?
Drift
not exposed
Vertical scale:
3 metres
2
1
0
No horizontal scale
Ferruginous sandstone
Sand
Clay
Silt
Cst.....Carstone
LzB.....Leziate Beds

Figure 5 Correlations between the more complete Dersingham Beds sequences in Norfolk

it to be the Kimmeridge Clay. Lamplugh (in Whitaker and Jukes-Browne, 1899) described the basal bed of the Carstone on the foreshore as a pebble bed set in a green clayey sand. The contact with the underlying clay was not at that time exposed, but he noted that "hard grey clay", presumed to be Snettisham Clay, had previously been seen in the spoil from the pier foundations. The pebble bed yielded cobbles of fossiliferous ironstones and pebbles with phosphatised ammonites. Casey (1961b, p.571) showed the phosphatised fauna to be of early Aptian age and that of the ironstones to be Barremian. The sources of these derived faunas were at that time unknown and deep trenches were therefore dug on Hunstanton Beach to re-expose the base of the Carstone and to enable the nature of the under-lying beds to be determined (Gallois, 1974). The composite section proved in these trenches is shown graphically in Figure 6. Ironstone nodules with the Barremian ammonite Paracrioceras were present in situ in the sands that were unconformably overlain by the Carstone. The sands are lithologically unlike the Snettisham Clay, but they can be matched with parts of the Roach of Lincolnshire. This correlation was confirmed by Morter (1975) who concluded that the non-ammonite fauna of the in situ ironstones was similar to that of parts of the Roach, and that it was probably mid Barremian in age. Correlation of the beach section and the Lincolnshire sequence with the cores of the BGS Hunstanton Borehole enabled 12.1m of beds to be assigned to the Roach in the borehole. The sequence is more complete beneath the The Wash and in Lincolnshire, due to the south-easterly overstep of the Carstone, and Borehole 72/78 proved 21.7m of the formation.

The beds assigned to the Roach in the Hunstanton, Skegness and 72/78 boreholes consist of a complex rhythmic sequence of inter-


Bed No.
Beach Sand
15+ m unfossiliferous Carstone in reef and cliff sections
4
Pebbly oolitic sand
3
Very pebbly sand with phosphatic nodules, containing derived Lower Aptian ammonites
Iron-grit nodules; shelly, sandy, phosphatic ironstone nodules with *Paracrioceras*: derived from Bed 1
Carstone
2
Oolitic pebbly clay, sandy in part
Scale metres
1
0·5
0
Erosion surface with burrowing
Upper nodules; widely spaced, very shelly, sandy, phosphatic ironstone nodules with ?*Paracrioceras*: *in situ*
Roach
1
Very fine-grained clayey sand
Lower nodules; widely spaced, sparsely shelly, sandy, phosphatic ironstone nodules: *in situ*
Outer Carstone reef
Exposed at low water beneath thin cover of beach sands
Exposed only in excavations

ig. 6 Graphic section showing the beds adjacent to the Roach-Carstone junction proved in trenches on Hunstanton Beach burrowed and interbedded lithologies made up of varying amounts of clay, chamosite mud, chamosite ooids (mostly limonitized), quartz sand and small pebbles of quartz and ironstone. The base of the formation has been taken at a minor erosion surface that separates the predominantly pebbly and oolitic clays of the Roach from the predominantly argillaceous, sparsely pebbly Dersingham Beds. The basal Roach erosion surface lies a little above the highest well developed reddish brown, smooth-textured clay of the Dersingham Beds. Thin beds of grey and reddish brown clay occur in the Roach, but the presence of thick beds of this lithology appear to be a useful distinguishing characteristic of the Dersingham Beds.

The Roach is almost entirely covered by drift deposits in Norfolk. It underlies much of the lowest part of the beach to the north of Hunstanton pier, but has been everywhere overlain by beach sand and gravel in recent years. Southwards from Hunstanton the formation is covered by till except for a small area near the Firs, on the south side of Hunstanton. There, a deep trench [678 392] revealed pebbly sandy clay beneath a cover of sandy downwash. This is the most southerly known occurrence of the Roach and it is presumed that the formation is overstepped by the Carstone in that area.

Although the ironstones obtained from the beach excavations at Hunstanton yielded a rich fauna, both in numbers and variety, the Roach in the boreholes is barren at many levels. It is probable that the fauna is concentrated, probably through selective preservation, in the more cemented lithologies and in the smoother textured clays. The fauna of the beach concretions is dominated by small bivalves (18 species) but also contains fragments of ammonites (*Hoplocrioceras* and

? Paracrioceras),gastropods (2 species and several small indeterminate forms), brachiopods (2 species), scaphopods and common wood fragments (Morter, 1975, pp.29-30).

Most of the fauna and flora is long-ranging. A few of the bivalves have Aptian affinities and suggest a Barremian or Aptian rather than an earlier age. Hoplocrioceras and Paracrioceras are known elsewhere from the Lower and Middle Barremian. One of the brachiopods, Rhynchonella parkhillensis Owen and Thurrell, has only previously been recorded from the Roach of the Lincolnshire outcrop (Owen and Thurrell, 1968, p.119). The presence of Middle Barremian ammonites in the Snettisham Clay (on which the Roach rests with only minor unconformity), and an apparently conformable junction with the Aptian Skegness Clay (see below) beneath The Wash and Lincolnshire suggests that the Roach preserved in Norfolk is late Middle to early Upper Barremian in age.

SKEGNESS CLAY AND SUTTERBY MARL

In the offshore area to the north-west of Hunstanton, the Roach is overlain by two argillaceous formations, the Skegness Clay and the Sutterby Marl, that are known only from boreholes in The Wash and at Skegness, and from a limited outcrop in Lincolnshire. These formations were deposited during the time interval represented by the unconformity between the Roach and the Carstone at Hunstanton. Both formations were probably formerly widespread in the district, but were removed by erosion and are now represented in the land area only by derived faunas in the basal pebble bed of the Carstone.

The relationships of the Skegness Clay to the Roach, Sutterby Marl and Carstone in The Wash area, including the positions of the indigenous and derived Aptian faunas, are summarised in Figure 7.

The Skegness Clay probably underlies much of the Norfolk side of the Wash. Offshore seismic evidence (Wingfield *et al*. 1979) suggests that it may approach within 2 km of Hunstanton Beach.

The Skegness Clay in Borehole 72/78 consists of 1.26m of medium and dark grey and brownish grey smooth textured clays with some bioturbation, pyritized trails and a sparse fauna of small bivalves, common crushed iridescent ammonites and rare gastropods and solitary corals. The junction with the underlying pebbly oolitic clays of the Roach is bioturbated, but sharp and apparently conformable. The ammonites have been identified by Dr R. Casey as *Aconeceras nisoides* (Sarasin), *Prodeshayesites germanicus* Casey, *P. bodei* (von Kuenen), *P. lestrangei* Casey and *P*. cf. *lestrangei*. The *Prodeshayesites* are especially common as derived phosphatized specimens in the basal pebble bed of the Carstone at Hunstanton beach. This assemblage is indicative of the earliest Aptian subzone, that of *Prodeshayesites bodei*, and the junction of the Roach and the Skegness Clay has therefore been taken to mark the Barremian-Aptian boundary (Gallois, 1975).

The non-ammonite fauna of the Skegness Clay has been identified by Mr A.A. Morter. It consists largely of small bivalves, most of which are long-ranging forms of *Camptonectes, Corbula, Grammatodon, Paranomia* and *Mesosacella*, that have also been recorded from the Barremian Tealby Beds and Roach.

The Sutterby Marl consists of very pale grey and pale yellowish grey, bioturbated, highly calcareous clays with a rich and diverse marine fauna of ammonites, belemnites, bivalves and brachiopods with rarer echinoids and solitary corals. It is about 3.2m thick in Borehole 72/78, and is probably overstepped by the Carstone about 5 km

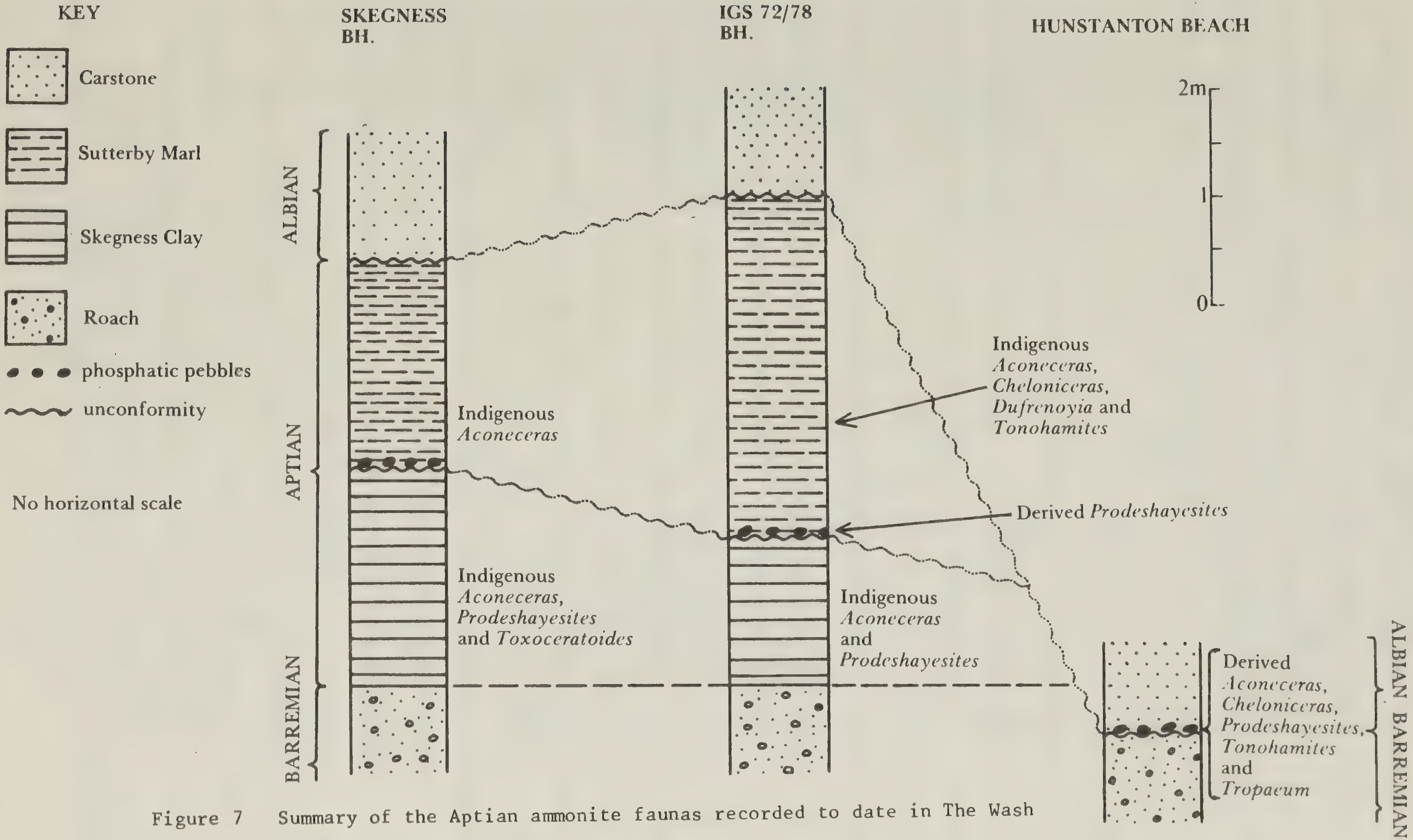

KEY
Carstone
Sutterby Marl
Skegness Clay
Roach
phosphatic pebbles
unconformity
No horizontal scale
SKEGNESS BH.
IGS 72/78 BH.
HUNSTANTON BEACH
2m
1
0
ALBIAN
APTIAN
BARREMIAN
Indigenous *Aconeceras*
Indigenous *Aconeceras*, *Prodeshayesites* and *Toxoceratoides*
Indigenous *Aconeceras*, *Cheloniceras*, *Dufrenoyia* and *Tonohamites*
Derived *Prodeshayesites*
Indigenous *Aconeceras* and *Prodeshayesites*
Derived *Aconeceras*, *Cheloniceras*, *Prodeshayesites*, *Tonohamites* and *Tropaeum*
ALBIAN BARREMIAN

Figure 7 Summary of the Aptian ammonite faunas recorded to date in The Wash

north west of Hunstation. The fauna in the borehole (Morter *in* Gallois and Morter, 1979) includes the bivalve *Aucellina aptiensis* (d'Orbigny) and the ammonites *Aconeceras nisoides* , *Cheloniceras* sp., *Dufrenoyia* sp. and *Tonohamites*?, and the belemnite *Neohibolites ewaldi* (von Strombeck). It is indicative of a late Lower Aptian or early Upper Aptian age.

CARSTONE, RED CHALK AND GAULT

The Albian stage is represented in Norfolk by three inter-related formations of markedly different lithology, the Carstone, Red Chalk and Gault. In the northern part of their outcrop and in their subcrop beneath The Wash, the Albian sediments consist of up to 19m of rusty brown and green, pebbly, limonite and chamosite-ooid-rich sandstone (Carstone) overlain by 1m to 5m of thinly interbedded pink limestone and brick red marl (Red Chalk). Between Dersingham and the Babingley River, the Red Chalk undergoes a rapid lithological change at outcrop and passes southwards first into grey calcareous clay with bands of soft chalky white limestone and then, in the Gayton area, into clay and calcareous clay (Gault). The Carstone thins southwards from Hunstanton to Dersingham in almost direct proportion to the thickening of the Red Chalk in the same direction, and from Dersingham southwards in proportion to the thickening of the Gault (Fig. 8). At the county boundary near Weeting, the Gault is over 17m thick and the Carstone consists of only 2m of oolitic clayey sand.

The striking colour contrast formed in Hunstanton cliffs by the rusty brown Carstone, the Red Chalk and the White Chalk, together with the richly fossiliferous nature of the Red Chalk, have attracted the attention of large numbers of geologists, both amateur and professional. In addition, the complex sedimentology of the Red Chalk

Late Jurassic - Mid Cretaceous

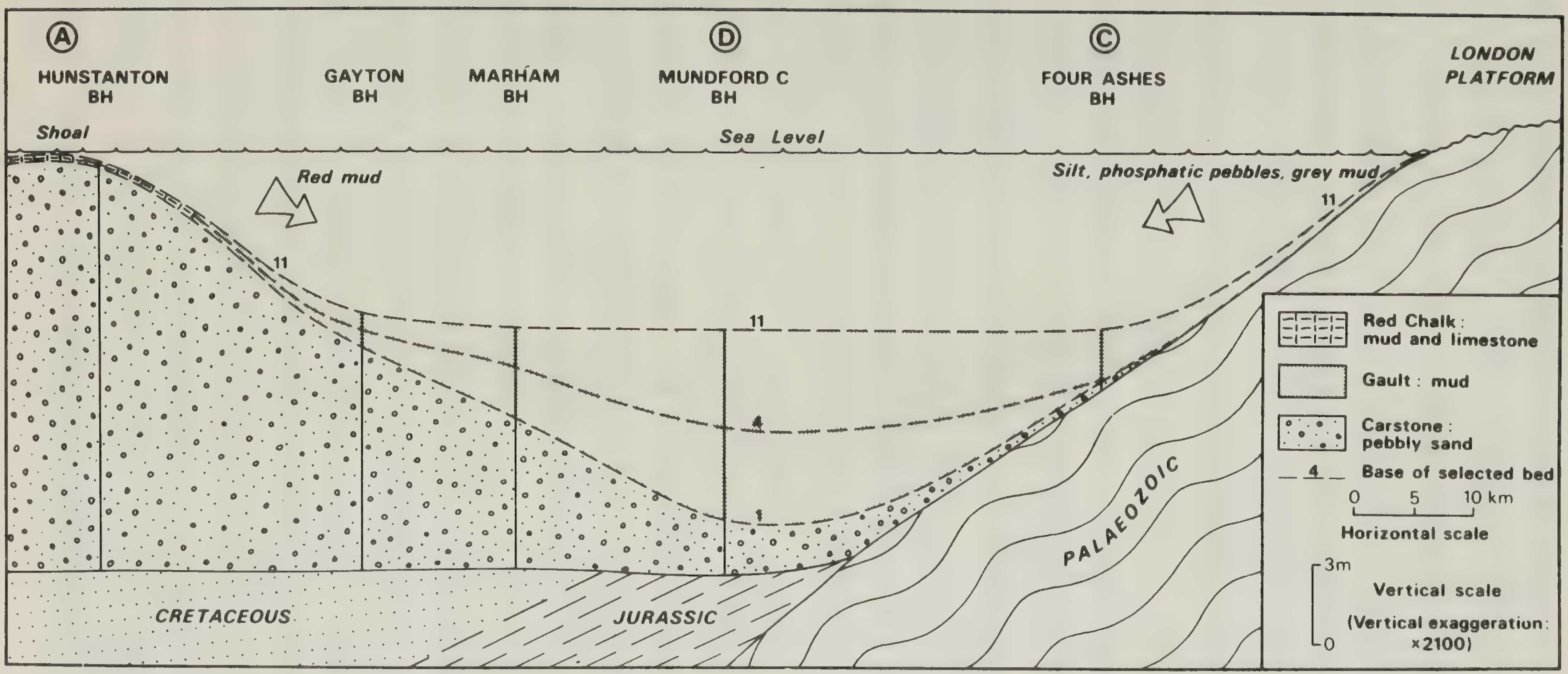

Ⓐ
HUNSTANTON BH
GAYTON BH
MARHAM BH
Ⓓ
MUNDFORD C BH
Ⓒ
FOUR ASHES BH
LONDON PLATFORM
Shoal
Sea Level
Red mud
Silt, phosphatic pebbles, grey mud
11
11
11
4
1
CRETACEOUS
JURASSIC
PALAEOZOIC
Red Chalk : mud and limestone
Gault : mud
Carstone : pebbly sand
4 Base of selected bed
0 5 10 km
Horizontal scale
3m
0
Vertical scale
(Vertical exaggeration: ×2100)

Figure 8. Reconstruction of the presumed depositional environment in the northern part of East Anglia immediately prior to the Upper Albian transgression.

and the difficulties of demonstrating its chronostratigraphical relationships to the Carstone and the Gault have generated a wealth of geological literature (see Larwood, 1961 for summary). In recent years, the sedimentology of the Red Chalk has been described by Jeans (1973, 1980); Clark (1964) examined belemnite orientations within it at Hunstanton. Casey (in Larwood, 1961, pp.290-291) re-examined the bivalve, gastropod and cephalopod faunas from Hunstanton and Owen (1979, p.580) has reviewed the significance of the ammonites in relation to the modern zonal and subzonal scheme for the Albian. The stratigraphical relationships of the Carstone, Gault and Red Chalk in Norfolk have ben described by Gallois and Morter (1982), and Wilkinson and Morter (1981) in a complementary study have described the ostracod sequences in the Gault. Andrews (1983) has described the sequence of micro- and macro-faunas in the Red Chalk.

Carstone

The Carstone has an almost continuous outcrop in Norfolk from Hunstanton to West Dereham, that is broken only by the wide drift-filled valleys of the rivers Babingley and Nar and by patches of glacial deposits. Between Hunstanton and Sandringham, the Carstone mostly crops out on a steep feature that is capped by Red Chalk and Chalk, and the outcrops of all three formations are strikingly apparent in freshly ploughed fields. The Carstone becomes thinner and more argillaceous southwards from Sandringham and the outcrop, in consequence, mostly occupies low ground. The formation is poorly exposed except for its type section in Hunstanton cliffs and in a small number of quarries dug for building stone and hardcore between there and the River Nar, notably at Heacham, Snettisham, Ingoldisthorpe, Dersingham and Sandringham. It continues to be worked for building stone at Snettisham [685 349] and is worked intermittently for hard-core in very extensive quarries [673 143 to 683 146] at Blackborough End. The unconformable junction with the Leziate Beds is especially well exposed at this last locality.

The maximum recorded thickness of the Carstone is 18.9m in the Hunstanton Borehole; a similar thickness is probably present in Hunstanton cliffs and foreshore. The formation thins north westwards beneath The Wash and is only 6.4m thick in Borehole 72/78. It thins southwards at outcrop and is 8.5m thick in the Gayton Borehole, 5.6m in the Marham Borehole and 2m at the county boundary.

The best exposed Carstone in eastern England is at Hunstanton. The whole of the formation is exposed in the foreshore and cliffs, with the exception of the basal beds and a thin bed in the middle part of the formation. Even the unexposed parts are overlain by only a thin covering of beach sand. The basal beds and the junction with the Roach (Fig. 6) have been exposed by trenching on the foreshore. The Carstone forms two prominent reefs on the beach, separated by a sand-covered slack that may conceal softer, possibly finer-grained or more clayey Carstone. The outer reef consists of dark greyish, green fine-grained, sparsely pebbly oolitic sandstone. Its outer edge is close to the base of the formation and phosphatized fragments of ammonites derived from the basal beds are common as beach pebbles. The inner reef is composed of sparsely pebbly and pebbly fine- and medium-grained, dark greyish green Carstone that weathers to the typical rusty brown. Its most striking feature is the manner in which it has been eroded; at beach level it appears to form an irregular collection of rounded lumps of sandstone, but when viewed from the adjacent cliff-top these can be seen to be separated by a remarkably uniform rectilinear set of joints that give rise to an out-crop pattern that was aptly likened by Whitaker (in Whitaker and Jukes-Browne, 1899, p.16) to an enormously magnified ichthyosaur paddle.

The upper 10m of the Carstone, including the junction with the Red Chalk, are well exposed in the cliffs between the Esplanade and St Edmund's Point. The Carstone there is composed of fine-, medium- and coarse-grained sands and pebbly sands; some levels in the upper part of the sequence, notably a 4.5m-thick band 3m from the top of the formation, are especially pebbly. The junction with the Red Chalk is well exposed; it is a gradational but rapid lithological change capped by a burrowed surface (Fig. 9). A band of widely spaced, pale brown phosphatized sand burrowfills forms a useful marker band 28 to 60 cm below the top of the Carstone.

The cliff section is deeply weathered with much secondary veining, cementation and liesegang precipitation of limonite and other iron materials. Planar cross-bedding, in units 0.3 to 0.5m thick, is discernible at several levels, but other sedimentary features are usually obscured by the limonitic weathering. Fresh cliff falls show the rock to be dark greyish green, oolitic (chamosite, limonite and limonitized chamosite), cross-bedded sandstone with large numbers of long, thin vertical burrows of the Arenicolites and Skolithos types. Such sections weather within a few months to produce the limonite-crust and boxstone weathering that is typical of the formation. At Hunstanton, in situ body fossils have only been recorded in the phosphatic sandy nodules close to the top of the formation.

Unweathered Carstone has been seen only in boreholes and even there limonitisation has occurred at a number of levels due to

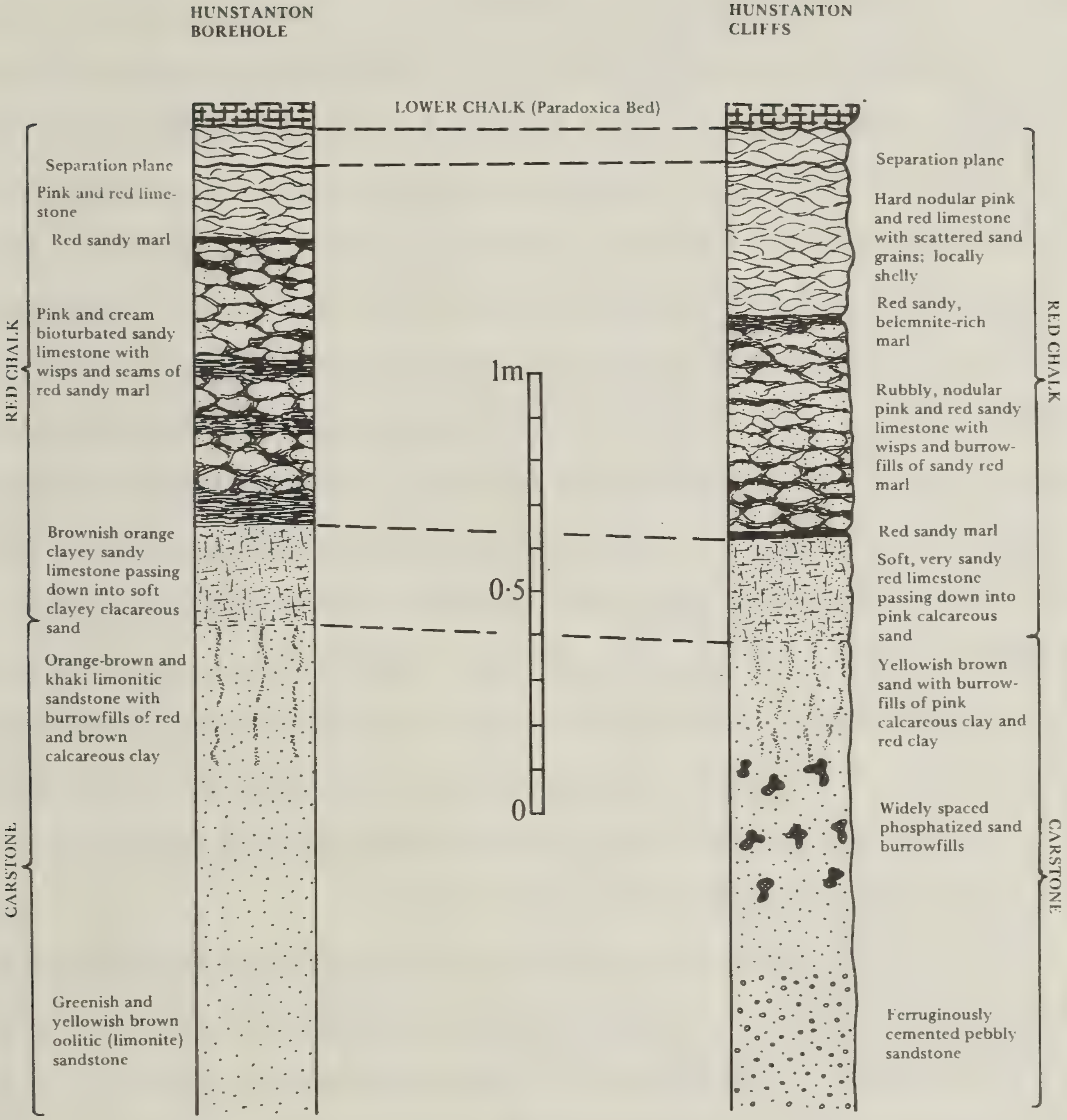

HUNSTANTON BOREHOLE
HUNSTANTON CLIFFS
LOWER CHALK (Paradoxica Bed)
Separation plane
Pink and red limestone
Red sandy marl
Pink and cream bioturbated sandy limestone with wisps and seams of red sandy marl
Brownish orange clayey sandy limestone passing down into soft clayey clacareous sand
Orange-brown and khaki limonitic sandstone with burrowfills of red and brown calcareous clay
Greenish and yellowish brown oolitic (limonite) sandstone
RED CHALK
CARSTONE
1m
0·5
0
Separation plane
Hard nodular pink and red limestone with scattered sand grains; locally shelly
Red sandy, belemnite-rich marl
Rubbly, nodular pink and red sandy limestone with wisps and burrow-fills of sandy red marl
Red sandy marl
Soft, very sandy red limestone passing down into pink calcareous sand
Yellowish brown sand with burrow-fills of pink calcareous clay and red clay
Widely spaced phosphatized sand burrowfills
Ferruginously cemented pebbly sandstone
RED CHALK
CARSTONE

Fig. 9 Lithological comparison of the highest Carstone and Red Chalk sequences in Hunstanton cliffs and the Hunstanton Borehole

oxidation within the zone (and former zones) of water-table fluctuation. The best-preserved section recorded to date is that in the cores of the Hunstanton Borehole where the bulk of the Carstone appears in hand specimen to be a relatively pure chamosite oolite with a partial cement of chamositic and/or sideritic mudstone. This is deceptive, however, and in thin section many of the ooids can be seen to consist of chamosite overgrowths on quartz grains. In all but a few samples, the total quartz content of the rock is 50% by volume. In the terminology developed by Taylor (1949) for the lithologically similar Northampton Sand ironstones they are 'chamosite oolite-sandstones'. Most of the ooids are partly or wholly oxidised; so too are the pebbles of clay ironstone and oolitic ironstone that are abundant in the more pebbly parts of the rock. Typical ooids consist largely of goethite and quartz with minor amounts of siderite, chamosite and montmorillonoid mineral (R.J. Merriman, pers. comm.). By contrast, the chamosite mud in the matrix is mostly fresh; in places a small part of it is replaced by siderite. This suggests either that some of the oxidation of the ooids was penecontemporaneous or that they have been preferentially oxidised at some later date.

None of the pebbles in the Carstone can be identified with confidence but most of the ironstones and mudstones can be matched with lithologies in the Roach and Dersingham Beds of Norfolk, or the Claxby Beds, Tealby Beds or Roach of Lincolnshire. Chalky limestone clasts may have been derived from the Tealby Beds. Clastic materials other than quartz and the pebbles noted above make up less than 2% by volume of the rock. Some unweathered Carstone samples from the borehole contain small fragments of metaquartzite, quartz-schist, acid-igneous rock of possible volcanic origin and grains of plagioclase and perthite (J.R. Hawkes, pers. comm.); these materials are presumed to have been derived from distant sources.

Burrows and cross-bedding are present at many levels in the Carstone, and may be ubiquitous, but their presence is almost always masked at outcrop by ferruginous weathering products. Burrows are especially abundant at the base of the formation and large numbers commonly penetrate the subjacent formation irrespective of its lithology. Where the underlying formation is a soft sand, as at Blackborough, a variety of larger, more irregular, burrows is present.

Fossils, other than plant debris and burrows, are rare in the Carstone and its age was in doubt until relatively recently. At Hunstanton, Casey (1961b, p.571) showed that the phosphatized ammonites from the basal beds were derived from the Lower Aptian. Species of indigenous terebratulid (Casey, 1967, p.91) and rhynchonellid (Owen _et al_.1968, p.518) brachiopods collected by Casey from the Cut-Off Channel at West Dereham are known elsewhere only from the Lower Albian Shenley Limestone of Bedfordshire and the highet part of the Carstone of Lincolnshire/Humberside. Casey (_in_ Casey and Gallois, 1973, p.11) also recorded the ammonites _Beudanticeras newtoni_ Casey, _Douvilleiceras mammillatum_ (Schlotheim) and _Leymeriella_ sp., indicative of the _Leymeriella tardefurcata_ and _Douvilleiceras mammillatum_ zones of the Lower Albian, in phosphatic nodules in the top part of the Carstone in the Cut-Off Channel. Teall (1875) had recorded a similar fauna, but including _Sonneratia kitchini_ Spath (indicative of the _mammillatum_ zone), from nodule beds at the same stratigraphical level in agricultural-phosphate workings in the West Dereham area. It is difficult to determine how closely these ammonites reflect the age of the deposit because although they are completely phosphatised, they appear to be little worn even though they are preserved in an abrasive, pebbly sand matrix. It seems reasonable to assume that this part of the Carstone is of *mammillatum* or post-*mammillatum* zone age.

At West Dereham, the Carstone is overlain by the Gault without any obvious major break in sedimentation. It contains abundant *Hoplites* spp. indicative of the *H. dentatus* zone; this suggests a *mammillatum* or early *dentatus* zone age for the latest Carstone there. At Hunstanton also, the conformable contact with the overlying Red Chalk, which contains indigenous *dentatus* zone ammonites, suggests that the upper part of the Carstone there is late Lower or early Middle Albian in age.

Red Chalk

The type section of the Red Chalk is the continous cliff that runs from Hunstanton Promenade [6725 4130] almost to Old Hunstanton [6786 4238], a distance of about 1.2 km. The formation is readily accessible at the northern end of the section where it falls to beach level, in cliff falls between there and the lighthouse, and in large fallen blocks.

Between Hunstanton and Snettisham the Red Chalk forms a thin but persistent marker band that is one of the most easily mapped in Britain. When the fields are ploughed, its soil brash together with that from the adjacent Carstone and Chalk, forms a colour and lithological contrast that is only slightly less muted than that in Hunstanton cliffs. Between Snettisham and Dersingham the colour of the Red Chalk becomes paler in a southerly direction until it is predominantly pink and cream coloured. At Dersingham, within a distance of less than one kilometre, the Red Chalk limestones pass laterally into red, pink and cream-coloured highly calcareous clays with nodules and thin bands of pink and cream limestone in their upper part. The lateral passage of the Red Chalk into the Gault at Sandringham is also rapid. There, the limestones and clays pass southwards into the brown sandy clay and grey, cream and brown silty clays of the Gault.

The Red Chalk thickens north-westwards from Hunstanton (1.1m of sandy limestone with marl wisps) into the Wash (3.2m of limestone with marl wisps in Borehole 73/78), and Lincolnshire (5.5m of interbedded limestone and red clay in the Skegness Borehole).

The Red Chalk has an extensive subcrop in Norfolk. It was proved in the deep onshore hydrocarbon boreholes at North Creake, South Creake, Saxthorpe, East Ruston and Somerton, in numerous offshore hydrocarbon boreholes (e.g. 78/22-2; Rhys, 1974) and in the BGS Trunch Borehole. It is presumed to underlie the whole of the county north of a line from Sandringham to Great Yarmouth.

Wiltshire (1859) and Seeley (1864) divided the Red Chalk at Hunstanton into three beds of limestone separated by two prominent seams of red sandy marl. There are numerous minor local variations in the sequence, but this general five-fold division can be recognised throughout the cliff exposure. The sequence, based on sections in the vicinity of the lighthouse [675 420], and its correlation with the sequence proved in the Hunstanton Borehole, is shown graphically in Figure 9.

The limestone contains a variety of primary sedimentary structures, such as burrows, borings and probable stromatolitic laminations, but many of these have been considerably modified by secondary lithification, cementation and mineral migration. Some idea of the degree of the complexity involved can be gained from the descriptions of these processes given by Jeans (1980).

The Red Chalk at Hunstanton has yielded a remarkably rich and diverse fauna, much of it from fallen blocks. However, the great variety of echinoderms, bryozoans, brachiopods, bivalves and ammonites, many beautifully preserved specimens of which can be seen in museum collections, reflect more than 150 years of patient collecting, rather than an obvious abundance in the rock. Le Strange (1974, pp.47-48), basing his observations on more than 50 years collecting at Hunstanton, notes that the commonest fossils in the Red Chalk are Inoceramus, Neohibolites and the brachiopod 'Moutonithyris' dutempleana (d'Orbigny). Cidarids and stems of Hemicrinus are relatively common, but other echinoderms are rare; well preserved ammonites and nautiloids are rare; corals, except for the solitary Podoseris, and gastropods are very rare.

Most of the fauna preserved in museum collections probably came from loose blocks and is not stratigraphically identifed, except as Red Chalk. Some material is identified in terms of the three limestone divisions of Wiltshire, but with varying degrees of reliability. Owen (1979, p.580) has summarised the ammonite evidence provided by these collections and has shown that Wiltshire's three limestones (lettered from the top downwards) can be correlated with the standard zonal/subzonal scheme for the Albian as follows:

Division A:	varicosum and auritus subzones of the inflatum Zone; ?rostratum Subzone of the dispar zone
Division B:	cristatum and orbignyi subzones of the inflatum Zone

?Divison B or C: *nitidus* Subzone of the *loricatus* Zone; *intermedius* and *meandrinus* subzones of the *lautus* zone

Division C: ?*spathi* Subzones of the *dentatus* Zone

Detailed collecting of the *in situ* non-ammonite assemblages by Mr A.A. Morter has enabled him to make detailed correlations with assemblages from the Gault of Norfolk, Suffolk and Cambridgeshire. His conclusions concerning the zones and subzones present at Hunstanton are closely similar to those of Owen; so too were Andrews' (1983) conclusions based on a study of the foraminifers and ostracods. All three authors agreed with earlier studies that have suggested that the Red Chalk at Hunstanton is a very condensed, but almost complete, representative of the Middle and Upper Albian.

Gault

The outcrop of the Gault in Norfolk can be traced from Sandringham southwards as far as West Dereham, at which locality the formation passes beneath the Recent deposits of Methwold Fens. It occupies low ground that is commonly covered by a veneer of sandy wash derived from the adjacent Chalk escarpment. The lower part of the formation, being farthest from the escarpment, has only a thin covering and is exposed in the deeper drains; the higher part is very rarely exposed. The outcrop is studded with numerous small pits (over 70 between Roydon and Gaytonthorpe Common alone) that were probably dug for agricultural marl and subsequently served as a water supply. The basal beds were well-exposed in the West Dereham area in Victorian times in large shallow pits dug for agricultural phosphate. All the exposures are now degraded, and few specimens have been preserved. Continuous cores have been obtained from the Gault close to its outcrop at Gayton and Marham and from a site-investigation borehole close to the county boundary at Hockwold-cum-Weeting. Cores were also obtained from the subcrop at Mundford and Great Ellingham.

In the Sandringham area, the most northerly point at which it can be recognised as a discrete argillaceous formation, the Gault consists of about 2m of pink and cream-coloured highly calcareous clay. This passes rapidly southwards into brown sandy clay and grey, cream-coloured and brown silty calcareous clays with thin beds of white and pink nodular chalky limestone in their upper part. These limestones are present as far south as Gayton; thin bands of white chalky limestones also occur at Bilney and Pentney, but these are at lower stratigraphical levels.

The formation thickens steadily southwards from Sandringham and is 9.0m thick at Gayton, 11.6m at Marham and 17.8m at Hockwold. This apparently regular southward thickening is a small part of a regional variation that is more complex, and as yet incompetely understood. In the subcrop, boreholes at Breckles, Rocklands and Great Ellingham indicate the presence of a broad tract of ground lying between the London Platform (in the south) and the Red Chalk depositional area (in the north) in which the Gault was probably originally about 15 to 20m thick, but where it has locally been reduced by erosion at the base of the Chalk. These regional variations in thickness result from a number of interacting factors and their pattern will undoubtedly become more complex as more borehole data become available.

At outcrop in Norfolk the Gault can be roughly divided into two parts; a lower part which weathers to medium grey and brown clays and an upper, more calcareous, part which weathers to pale and very pale grey clay with thin bands of soft argillaceous limestone. The Lower

Gault and the lower part of the Upper Gault are made up of small-scale rhythms, mostly 1 to 2m thick. Each rhythm begins with a medium or dark grey, shelly, pebbly, silty mudstone or muddy siltstone, rich in inoceramid prisms, oysters, belemnites, exhumed phosphatized burrow-fills, and water-worn phosphatic pebbles, that rests on a partially phosphatized and glauconitized, burrowed surface. This basal bed passes up into medium and pale grey calcareous mudstones by a decrease in the coarser clastic (including bioclastic) content and an increase in calcium carbonate. This lithological change is commonly accompanied by a decrease in faunal diversity and numbers. The upper part of the Upper Gault shows weakly developed rhythms that are made up of paler, more calcareous mudstones (richer in coccoliths) than those of the Lower Gault and the sequence contains fewer major erosion surfaces.

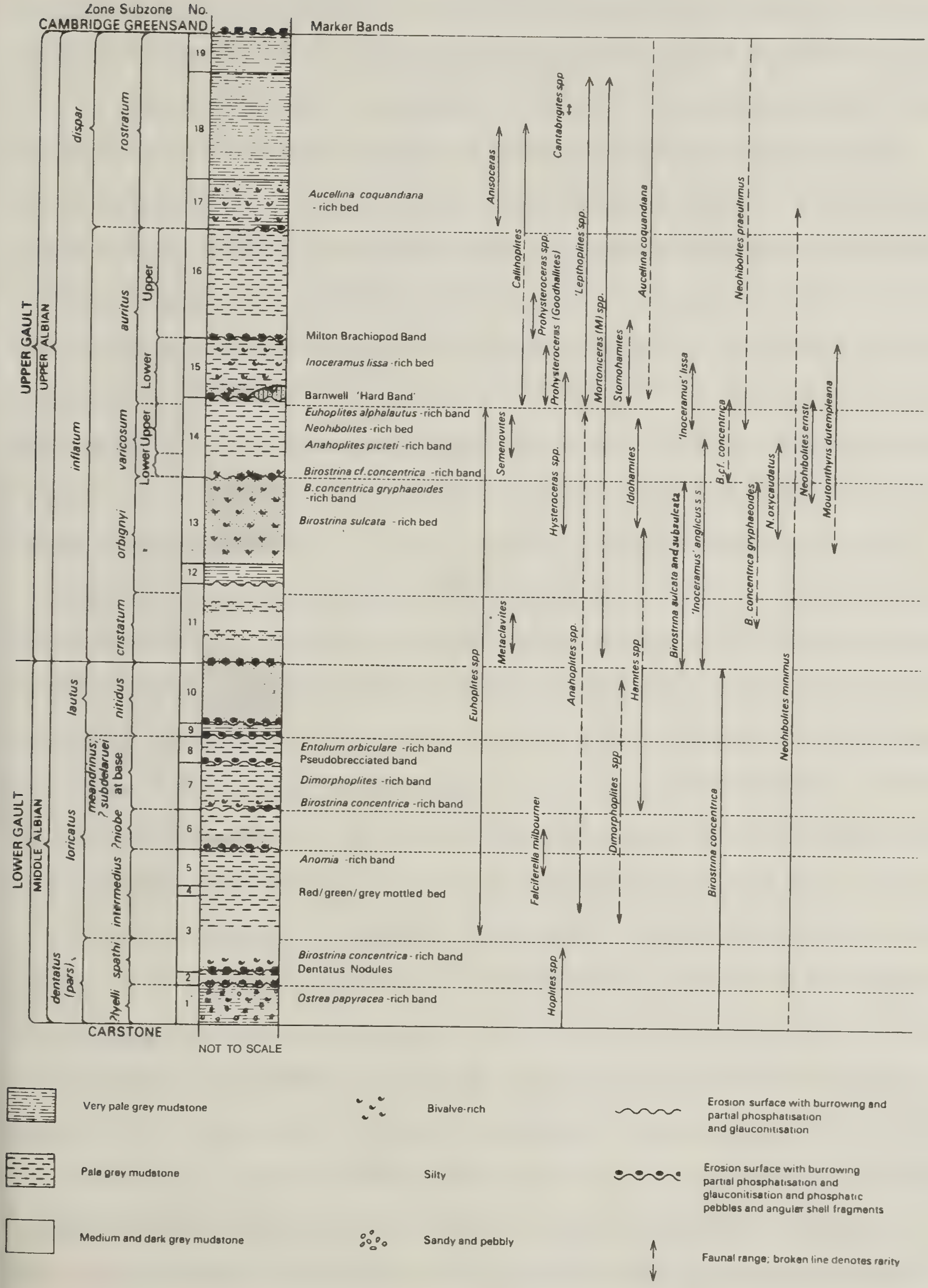
The main difficulty in attempting correlations within the Gault is that of recognising the bases of those individual rhythms that are erosive and so may locally cut out all or part of the underlying rhythms. In the Gault sequences proved in cored boreholes in Norfolk, correlations can be made with confidence over relatively large distances by comparing the sequences of lithological and faunal events (Fig. 10). These comparisons have enabled a standard sequence of 19 distinctive beds to be devised that is applicable to the Gault of the central and northern parts of East Anglia (Gallois and Morter, 1982). Bed 19, the youngest in the sequence, has been recorded only in the Gayton Borehole.

The recognition of zones and subzones is difficult in borehole cores in the Gault, despite the generally fossiliferous nature of the formation, because of the limited amount of material available from any particular horizon. Additionally in Norfolk, where the sequence is poorly exposed and attenuated in comparison with other parts of England, very few of the characteristic ammonite assemblages have been recognised at outcrop. The subzonal/zonal scheme shown in Figure 10 has, therefore, been determined from the faunal data obtained from a large number of boreholes, exposures and museum collections from throughout East Anglia. A detailed description of the faunal sequence of the standard succession is given, bed by bed, by Morter (*in* Gallois and Morter, 1982).

The Gault contains a rich marine fauna dominated by bivalves, but includes relatively common solitary corals, serpulids, gastropods, scaphopods, ammonites, belemnites, crinoids and echinoids, together with an abundant microfauna of ostracods and foraminifers. Ichnofossils are represented by common *Chondrites*, possible thalassinoid burrows and a variety of trails. Unfortunately, little of this fauna can be collected at outcrop in Norfolk.

SUMMARY OF GEOLOGICAL HISTORY

After a period of erosion in the late Jurassic, the sea returned to Norfolk in the mid Volgian. The basal bed of the Roxham Beds rests with marked unconformity on a wave-cut platform of Kimmeridge Clay. The coarse pebbly lithology of this basal bed and its abundant and varied fauna show that it was deposited in a well-aerated, current- or wave-agitated marine environment; the presence of long, vertical *Skolithos*-type burrows penetrating the underlying Kimmeridge Clay indicate that the water was initially very shallow, possibly intertidal. Water depth increased with time and the basal pebble bed was replaced by intensely bioturbated, glauconitic and pyritic sands with erosion surfaces marked by phosphatic nodule/pebble beds. The peak of


Zone Subzone No.
CAMBRIDGE GREENSAND
Marker Bands
UPPER GAULT
UPPER ALBIAN
LOWER GAULT
MIDDLE ALBIAN
dispar
rostratum
inflatum
auritus
Upper
Lower
varicosum
orbignyi
cristatum
lautus
nitidus
loricatus
meandrinus; ? subdelaruei at base
?niobe
intermedius
dentatus (pars)
spathi
?lyelli
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
Aucellina coquandiana - rich bed
Milton Brachiopod Band
Inoceramus lissa -rich bed
Barnwell 'Hard Band'
Euhoplites alphalautus -rich band
Neohibolites -rich bed
Anahoplites picteti -rich band
Birostrina cf. concentrica -rich band
B. concentrica gryphaeoides -rich band
Birostrina sulcata - rich bed
Entolium orbiculare -rich band
Pseudobrecciated band
Dimorphoplites -rich band
Birostrina concentrica -rich band
Anomia -rich band
Red/green/grey mottled bed
Birostrina concentrica - rich band
Dentatus Nodules
Ostrea papyracea -rich band
CARSTONE
NOT TO SCALE
Anisoceras
Callihoplites
Prohysteroceras spp.
Prohysteroceras (Goodhallites)
Cantabrigites spp
'Lepthoplites' spp.
Mortoniceras (M) spp.
Stomohamites
Aucellina coquandiana
Neohibolites praeultimus
Semenovites
Hysteroceras spp.
Idiohamites
'Inoceramus' lissa
B. cf. concentrica
N. oxycaudatus
Neohibolites ernsti
Moutonithyris dutempleana
Birostrina sulcata and subsulcata
'Inoceramus' anglicus s s
B. concentrica gryphaeoides
Metaclavites
Euhoplites spp
Anahoplites spp.
Hamites spp
Neohibolites minimus
Dimorphoplites spp
Falciferella milbournei
Birostrina concentrica
Hoplites spp
Very pale grey mudstone
Pale grey mudstone
Medium and dark grey mudstone
Bivalve-rich
Silty
Sandy and pebbly
Erosion surface with burrowing and partial phosphatisation and glauconitisation
Erosion surface with burrowing partial phosphatisation and glauconitisation and phosphatic pebbles and angular shell fragments
Faunal range; broken line denotes rarity

ig 10 Generalised vertical section of the Gault of East Anglia showing the main lithological and faunal features phosphate and glauconite production occurred in the Runcton Beds and earliest Mintlyn Beds in intensely bioturbated and winnowed sands that were deposited in a current-swept, probably shallow, clear sea.

The bulk of the Mintlyn Beds was laid down in less energetic environments. Thin undisturbed bands of glauconitic clay indicate quiet conditions at some levels, and cross-lamination shows that weak currents were present at others. The fauna is wholly marine but although the total number of ammonite and bivalve species is high, the diversity at most levels is low. Kelly (1977) concluded that the bivalves were indicative of shallow marine environments in which the assemblages were controlled by the substrates.

The geographical distribution of the Leziate Beds suggests that they were deposited as a linear sand body bounded to the east or south-east by land and to the west and north-west by a shallow sea in which the predominantly muddy sediments of the Claxby Beds were being deposited. The sparse faunal evidence shows that the Leziate Beds are marine and this is confirmed by the burrows and sedimentary structures. The cross-bedding orientations show evidence of tidal currents and the overall pattern is consistent with that of a prograding sand body that accreted by shoreward (eastwards) migration of sand under tidally influenced conditions in which the flood tides were stronger than the ebbs. The presence of oscillation ripples with clay drapes in the youngest part of the Leziate Beds may indicate that the sands locally accreted to the point where their upper surface was in the intertidal zone.

The faunal, lithological and field relationships all suggest that the basal Dersingham Beds transgressed across the Leziate Beds in an easterly or south easterly direction. The lateral passage within the

Dersingham Beds from predominantly arenaceous in the Dersingham area to argillaceous at Hunstanton, and into the argillaceous Tealby Beds beneath The Wash mimics the lithological change in the same direction in the underlying beds (the Leziate Beds passage into the argillaceous Claxby Beds) except that the change from argillaceous to arenaceous occurs a little farthr south (Heacham instead of beneath The Wash) in the Dersingham Beds. Moderately diverse marine faunas occur in the basal beds of the Dersingham Beds and at many other levels in the formation. These faunas and the sedimentary evidence suggest deposition in shallow, nearshore bans and sand flats (sands), and lagoons and a shallow sea with partially restricted circulation (muds).

The pebbly argillaceous Dersingham Beds of the Hunstanton area are unusually poorly sorted for a marine sediment. The pebbles appear to have been introduced into a shallow muddy sea (possibly lagoonal) either by river floods breaking down riverine or estuarine gravel bars, or by storms dispersing beach shingle or offshore gravel bars. The varied and mostly thick-shelled nature of the fauna suggests that much of it was also swept into the depositional area with the gravel.

In Lincolnshire, the Tealby Beds contain a richer and more varied marine fauna than the Dersingham Beds indicating that more open marine conditions were present in Lincolnshire than in Norfolk at that time.

The Roach overlies the Dersingham Beds and Tealby Beds with minor unconformity, but its lithologies and fauna are so similar to those of the underlying beds that it can be considered to form an unbroken rhythmic sedimentary sequence with them and to have been deposited in the same range of shallow, near-shore transgressive/regressive environments.

Taken together, the Skegness Clay and Sutterby Marl represent a steady transgression that replaced the restricted environments of the Roach with a shallow open marine environment, initially with a partially restricted circulation (Skegness Clay) and then with an open shelf environment (Sutterby Marl).

The London Platform appears to have undergone rejuvenation in the Aptian, but this was of a local nature that may have been related to faulting around its margins. As a result, the Carstone sea appears to have re-occupied a broad coastal plain that had become emergent in what is now Norfolk during the late Aptian. The lithological and thickness variations in the Carstone suggest that it formed an offshore bar composed largely of sand, ooids and pebbles in the Hunstanton area, with marine glauconitic sands and clayey sands on its southern (Norfolk) side and marine sands on its north-western (Lincolnshire) side. With time, this bar was overlain at Hunstanton by the highly condensed Red Chalk limestones. Deeper water to the north and south appear to have acted as sediment traps in which more-argillaceous Red Chalk and Gault clays were deposited respectively (Fig. 10). The most condensed Red Chalk sequence overlies the thickest development of the Carstone and was probably deposited in the shallowest, most current-swept environment. Jeans (1973, 1980) has described algal stromatoliths in the Red Chalk at Hunstanton and concluded that the upper part of the formation was deposited in the photic zone.

The fauna of the Gault is fully marine at all stratigraphical levels and at no time do the Red Chalk shallows to the north or the London Platform to the south appear to have restricted water movements. The rhythms in the Gault contain sedimentary and faunal evidence of the repetitive replacement of high-energy (presumed shallow water) by low-energy (presumed deeper water) marine environments. The maximum extent of transgression in the Gault may have been at the onset of the Upper Gault when the London Platform was finally inundated. The highly calcareous highest part of the Gault, with its fauna restricted almost solely by oysters, appears to represent the last regression before the great Cenomanian transgression that brought pelagic chalk sedimentation to the whole of eastern England.

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A GUIDE TO THE GEOLOGY OF SOUTH-EAST SUFFOLK

S.J. Mathers*, J.A. Zalasiewicz* & P.S. Balson*

CONTENTS

1. Pre-Pliocene Deposits
2. Coralline Crag
3. Post-Coralline Crags

3a. Red Crag

3b. Norwich Crag

4. Kesgrave Sands and Gravels
5. Anglian Glaciation
6. Ipswichian Interglacial
7. Flandrian
8. References

TABLES

1. Generalised stratigraphy of south-east Suffolk
2. Classification of the Coralline Crag of Prestwich (1871a) and Wood and Harmer (1872) from Burrows (1895a)

FIGURES

1. Simplified Geology of south-east Suffolk
2. Distribution of the Coralline Crag
3. Distribution of Coralline Crag facies after Balson (1981a)
4. Distribution of the Red Crag 'stages' after Harmer (1902)
5. Correlation of the Crag deposits of south-east Suffolk [correlation with the Netherlands modified after Zagwijn (1975)]
6. Schematic diagram of the Crag deposits of the area around Chillesford, Aldeburgh and Sizewell. Lithostratigraphy from Zalasiewicz & Mathers (in prep.); biostratigraphical stages at Sizewell after Funnell (1983)

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1. PRE-PLIOCENE DEPOSITS

The Plio-Pleistocene sediments which cover much of south-east Suffolk (Table 1 and Figure 1) are underlain by both Eocene and Cretaceous strata. The latter rest directly on Lower Palaeozoic rocks proved in several deep boreholes.

In the north and west of Suffolk the Upper Chalk is exposed at surface and directly underlies the Plio-Pleistocene deposits. When traced south-eastwards down dip the Eocene Woolwich and Reading Beds and London Clay form successive subcrops beneath the younger deposits. In the Ipswich-Felixstowe area these Eocene beds dip gently towards the south-east, whereas further north around Aldeburgh the same beds dip due east. Existing borehole data does not reveal any major zones of displacement within the Eocene strata of south-east Suffolk although Pleistocene faulting has been advocated by Bristow (1983) in mid-Suffolk to explain the steep linear margins of some of the Pleistocene Crag basins.

Following the deposition of the London Clay the area is thought to have been emergent and subject to subaerial processes prior to the onset of Pliocene Crag deposition. A marine transgression during the Miocene is however indicated by the presence of phosphatic concretions containing a Miocene fauna (Suffolk boxstones), reworked into the base of the Plio-Pleistocene Crag.

2. CORALLINE CRAG

Brief History of Research

The Coralline Crag consists of marine shelly calcarenites of Pliocene age resting on the London Clay (Eocene) in south-east Suffolk (Fig. 2).

TABLE 1 GENERALISED STRATIGRAPHY OF SOUTH EAST SUFFOLK

ESTUARINE SILTS & CLAYS	FLANDRIAN	HOLOCENE
INTERGLACIAL DEPOSITS	IPSWICHIAN	PLEISTOCENE
GLACIAL DEPOSITS (dominantly Lowestoft Till)	ANGLIAN	
SOL LESSIVE	CROMERIAN	
KESGRAVE SANDS and GRAVELS	BEESTONIAN	
NORWICH CRAG	BRAMERTONIAN	
	BAVENTIAN	
	?ANTIAN	
	?THURNIAN	
RED CRAG	PRE-LUDHAMIAN	
CORALLINE CRAG	PLIOCENE	TERTIARY
LONDON CLAY WOOLWICH and READING BEDS	EOCENE	
CHALK GAULT CLAY	CRETACEOUS	
BASEMENT	LOWER PALAEOZOIC	

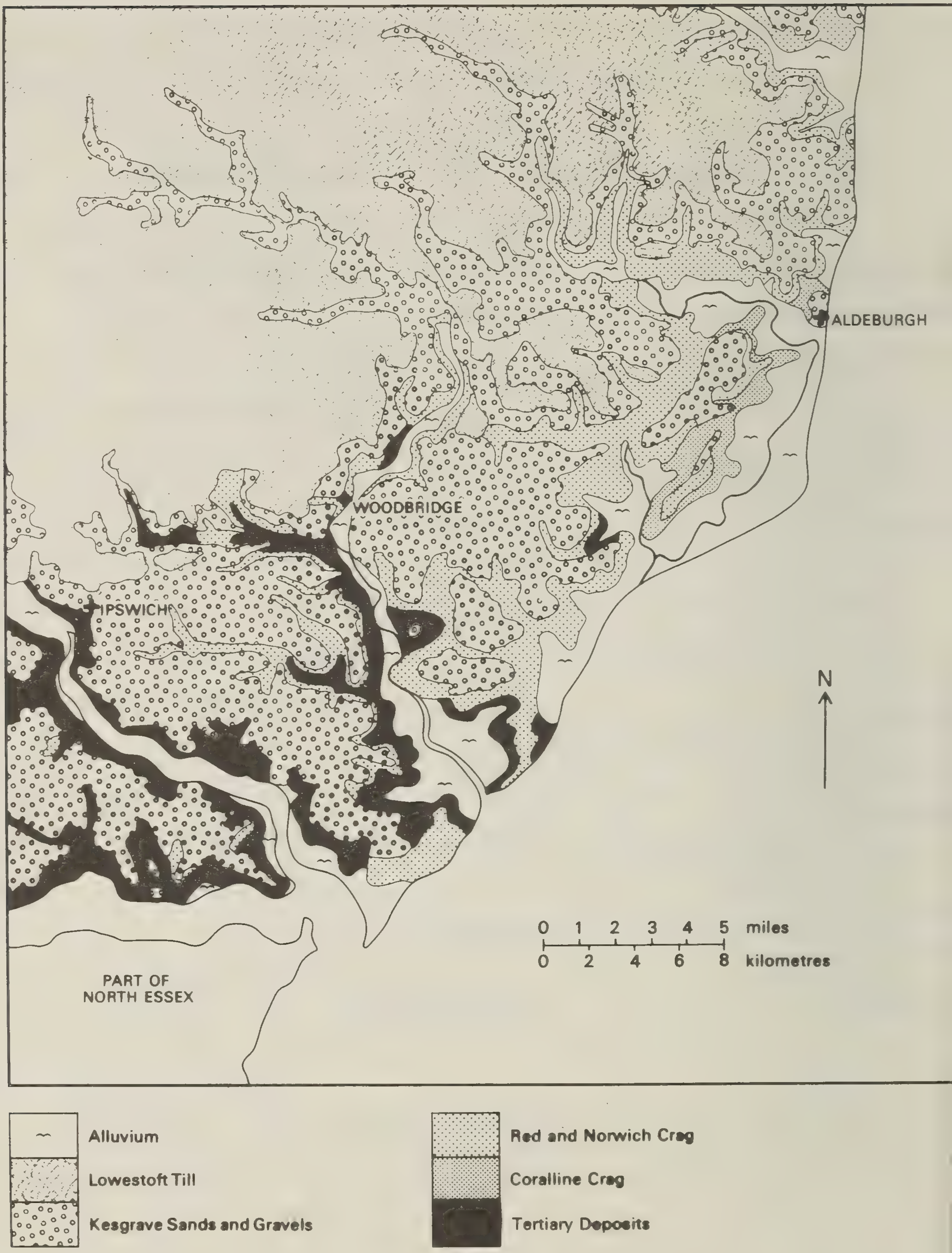

ALDEBURGH
WOODBRIDGE
IPSWICH
N
0 1 2 3 4 5 miles
0 2 4 6 8 kilometres
PART OF
NORTH ESSEX
Alluvium
Lowestoft Till
Kesgrave Sands and Gravels
Red and Norwich Crag
Coralline Crag
Tertiary Deposits

Fig. 1 Simplified geology of south-east Suffolk

South-East Suffolk

The Coralline Crag was first proposed as a distinct unit by Charlesworth (1835) who subdivided the Crags (shelly sands) of East Anglia into a lower Coralline Crag or 'coral'-bearing Crag and an upper, Red Crag. The term Coralline Crag is misleading as it results from the identification by Charlesworth of the abundant bryozoan fossils as corals. The subdivision of the Crags initially proposed by Charlesworth (1835) was questioned by some authors, including Woodward (1835, 1836) and Desnoyers (1838) whilst others, including Fitch (1835) and Lyell (1839) supported it. Realisation that the Coralline Crag contained abundant bryozoans rather than corals resulted in many alternative names being suggested, Bryozoan Crag, Polyzoan Crag, White Crag, Lower Crag, Lowest Crag and Suffolk Crag (Jones and Parker 1864; Bell and Bell 1871, 1872; Dalton and Whitaker 1886 and Burrows 1895b). Despite all these suggestions as more appropriate names for the deposits the term Coralline Crag has remained to the present day.

Many of the nineteenth century studies of the Coralline Crag concentrated upon the production of palaeontological monographs, e.g. Wood (1848-1882), and extensive lists of fossil species, e.g. Bell and Bell (1871, 1872). Reid (1890) gives a useful review of this work. These studies built up a very detailed picture of the range of species present. However, little quantitative work on the faunas or their environment of deposition was attempted until Prestwich (1871a) proposed a bio- and lithostratigraphical classification of the Coralline Crag. Prestwich (1871a) subdivided the Coralline Crag into a series of eight zones [which he referred to as a-h (see Table 2)]. He cited sedimentological as well as palaeontological criteria by which many of these zones could be recognised and quoted localities at which the different zones were exposed. Prestwich envisaged the

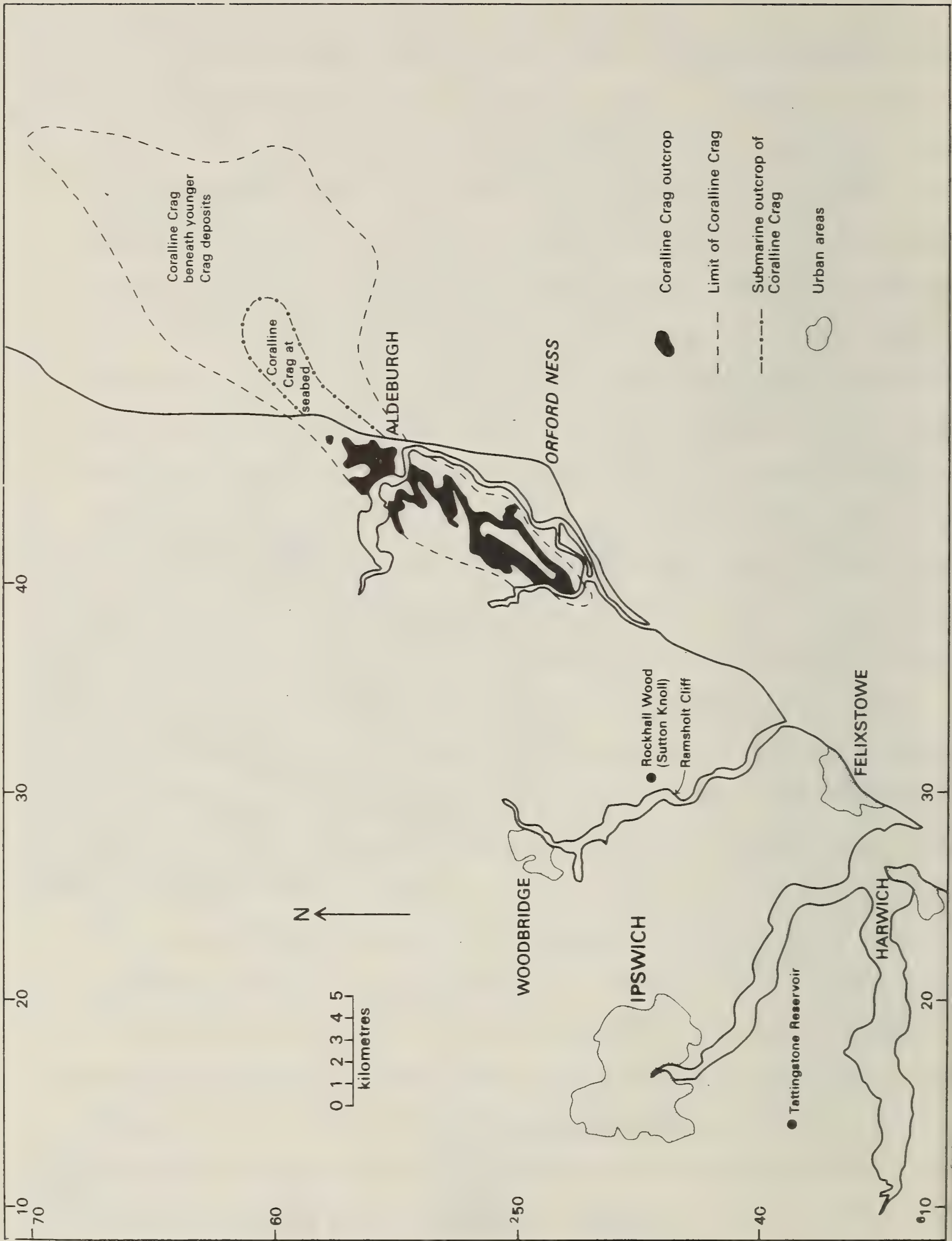

Coralline Crag beneath younger Crag deposits
Coralline Crag at seabed
ALDEBURGH
ORFORD NESS
Coralline Crag outcrop
Limit of Coralline Crag
Submarine outcrop of Coralline Crag
Urban areas
Rockhall Wood (Sutton Knoll)
Ramsholt Cliff
FELIXSTOWE
WOODBRIDGE
IPSWICH
HARWICH
Tattingstone Reservoir
N
0 1 2 3 4 5
kilometres
10
20
30
40
70
60
250
40
10

Fig. 2 Distribution of the Coralline Crag

succession as representing a marine transgression leading to deep water (150-300m) conditions during the deposition of zone 'e' followed by regression which culminated in emergence, terminating the deposition of the Coralline Crag.

In the following year Wood and Harmer (1872) offered an alternative to Prestwich's scheme. They doubted the stratigraphical continuity of many of Prestwich's zones and regarded his estimates of maximum water depth as excessive. Instead, they proposed a threefold division of the Coralline Crag (Table 2) and regarded the uppermost part of the sequence as being reworked from their lower divisions. Harmer (1900a) suggested that the Coralline Crag should be assigned to a new Pliocene stage, the Gedgravian. In addition Harmer (1898, 1902, 1910) developed his own model for the deposition of the Coralline Crag, suggesting it formed as a series of nearshore shell banks influenced by tidal currents. Since Harmer's work the Coralline Crag has not been extensively studied until recently. Subsequent publications by Boswell (1927, 1928) in Geological Survey Memoirs and Baden-Powell (1953, 1955a, 1955b and 1960) served only to review the existing literature.

Recent Work

Palaeontological studies of the Coralline Crag in recent years have been concerned with the Foraminifera (Carter 1951), Ostracoda (Wilkinson 1980), Bryozoa (Balson 1981a, 1981b and Balson and Taylor 1982) and Pollen (Andrew and West 1977).

A new classification of the Coralline Crag based on sedimentological and palaeontological criteria has recently been developed by Balson (1981a, 1981b and in prep) (Figure 3). Four

AFTER PROFESSOR PRESTWICH					AFTER MESSRS. S.V.WOOD, JUN., AND F.W.HARMER	
Zone		Thickness	Character of beds	Localities		
UPPER DIVISION 36' 0''	h	6'0''	Sand and comminuted shells	Sudbourne, Gedgrave	3'''	Bed reconstructed out of 3'' comminuted
	g	30'0''	A series of beds consisting almost entirely of comminuted shells and remains of *Bryozoa* forming a soft building stone. False stratification and oblique bedding are its constant characters	Sutton Sudbourne, Gedgrave, Iken, Aldborough	3''	Solid bed of Molluscan remains, with various species of *Bryozoa*. "The *Bryozoa* rockbed of the Coralline Crag"
LOWER DIVISION 47' 0''	f	5'0''	Sand with numerous entire shells and seams of comminuted shells	Sutton, Iken, Sudbourne, Gomer		
	e	12'0''	Sands with numerous *Bryozoa*, often in the original position of growth, and some small shells and *Echini*	Sutton, Broom Hill		
	d	15'0''	Comminuted shells, large entire or double shells, and bands of limestone in the upper part	Sutton, Broom Hill, Sudbourne, Iken, Tattingstone	3'	Calcareous sands, in some places more or less marly, rich in Molluscan remains. "The shelly sands of the Coralline Crag"
	c	10'0''	Marly beds with numerous well-preserved and double shells, often in the position in which they lived	Sutton, Ramsholt		
	b	4'0''	Comminuted shells. Cetacean remains, *Bryozoa*	Sutton		
	a	1'0''	Phosphatic nodules and Mammalian remains	Sutton		
Total		83'0''			Total thickness 60 feet	

Table 2 Classification of Coralline Crag of Prestwich (1871a) and Wood and Harmer (1872), from Burrows (1895a)

facies are recognised in the Coralline Crag. The characteristics of these facies are as follows:

Nodular Phosphorite Facies

A thin but widespread remanie bed of phosphatic nodules with occasional vertebrate teeth and bones occurs at the base of the Coralline Crag, resting on London Clay (Balson 1980). The deposit varies from 0.4m thick to only a thin layer of pebbles. This horizon was exploited, along with the Red Crag phosphorite deposits, as a source of fertilizer in Victorian times.

Silty Sand Facies (Facies A, Figure 5)

This facies occurs at Tattingstone, Ramsholt, Sutton and in the Gedgrave area (where it is overlain by facies B). At Tattingstone the deposit comprises skeletal shelly sands in which, owing to bioturbation or wave action, few sedimentary structures are preserved. The fauna is dominated by eschariform bryozoans. At Ramsholt and Sutton the sediments comprise silty sands with eschariform (erect, laminar forms) and celleporiform (erect and encrusting, globular forms) bryozoans dominant.

Sandwave Facies (B)

This facies comprises well-sorted bioclastic sands which are preserved between Sudbourne and Gedgrave and are characterised by large sets, up to 3m thick, of foreset laminae. These deposits are regarded as the product of the migration of submarine sandwaves. Palaeocurrent studies (Balson 1981a), confirm a strong unimodal current direction towards the south-west The *in situ* bryozoan faunas are dominated by eschariform, cellariiform (erect, branching, flexible forms) and celleporiform types.

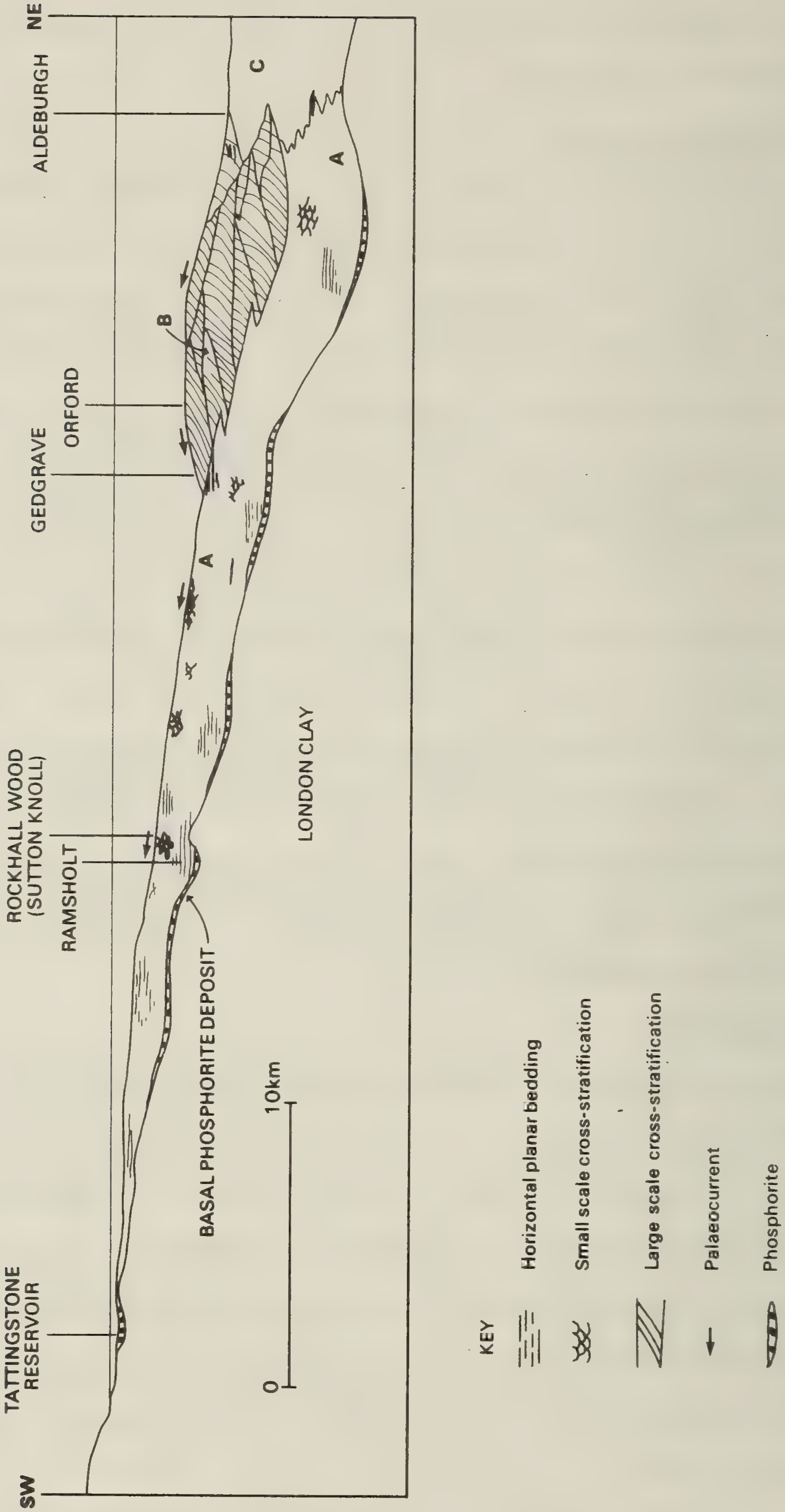

SW
NE
TATTINGSTONE RESERVOIR
ROCKHALL WOOD (SUTTON KNOLL)
RAMSHOLT
GEDGRAVE
ORFORD
ALDEBURGH
A
B
A
C
LONDON CLAY
BASAL PHOSPHORITE DEPOSIT
0
10km
KEY
Horizontal planar bedding
Small scale cross-stratification
Large scale cross-stratification
Palaeocurrent
Phosphorite

Fig. 3 Distribution of Coralline Crag facies after Balson (1981a)

Skeletal Sand Facies (C)

The deposits of facies C comprise coarse skeletal shelly sands with little minerogenic material, which are developed in the Aldeburgh area. The deposits contain abundant burrows and silt drapes, with gently inclined and horizontal stratification present. The relationship betwen these deposits and those of facies B is uncertain. They contain an extensive *in situ* fauna of bryozoans. The fauna is interpreted as a winnowed deposit which formed seaward (?upcurrent) of the sandwave complex.

Form and Distribution

The distribution of the Coralline Crag of south-east Suffolk is shown in Figure 2. The main body of sediment occurs between Aldeburgh and Gedgrave. The Coralline Crag forms submerged rocks along the coast between Sizewell and Thorpeness as originally noted by Lyell (1839) and continues offshore to the north-east (Lees 1982). To the south-west of the main outcrop the Coralline Crag has been recorded on Boyton marshes. Isolated outcrops of Coralline Crag are present around Ramsholt and Sutton (Rockhall Wood = Sutton Knoll of previous authors) and farther west at Tattingstone. Thin Coralline Crag has also been reported at Waldringfield (Whitaker 1885) and at Trimley (Wood and Harmer 1872).

The main body of the Coralline Crag comprises up to 25m of deposits, which rest on London Clay. The form of the London Clay surface over this area is shown in Dixon (1979) and Carr (1967). The Coralline Crag is thickest where it fills a depression running northwards from Orford: this feature is regarded by Carr (1967) as a fluvial channel cut into the London Clay surface prior to the onset of

Coralline Crag sedimentation. Although this is possible, early Pliocene marine erosion might equally have been responsible.

Within the upper part of the Coralline Crag aragonitic shell material is absent, although moulds of aragonitic fossils are sporadically preserved. This selective dissolution of aragonite is believed to have provided the calcium carbonate for lithification of the sediment into a porous limestone, which is locally hard enough for use as a local building stone. This lithified upper portion is equivalent to "bed 3" of Wood and Harmer (1872) - the so-called Bryozoa Rock-bed of these and later authors. Although of no real stratigraphical significance, this lithification is believed to be facies - specific and mainly affects those facies which were deposited as clean porous skeletal sands (Balson 1983).

The Coralline Crag outcrop is elongated in a direction oblique to the bedrock contours, but this may well be an original depositional feature (Harmer 1898). In detail, parts of the outcrop form linked en echelon segments which possibly reflect the original form of the deposits (Balson 1983). The shape of the outcrop closely resembles that of present-day sand ridges off the Norfolk coast. Mapping of the Coralline Crag and the Red Crag show the two to be geographically almost mutually exclusive, reflecting the fact that the Coralline Crag sediments persisted as a positive topographical ridge long after their deposition. This concept was also advanced by Dixon (1979). An ancient cliff of Coralline Crag exposed near Sutton at Rockhall Wood also suggests that the Coralline Crag was emergent during the deposition of the Red Crag.

Age and Correlation

The Coraline Crag is most readily correlated with the Pliocene sequence of Belgium. On the basis of molluscs (Reid 1890; Harmer 1900a, 1900b, 1910 and 1918) and bryozoans (Lagaaij 1952) a correlation with the Belgian 'zone a Isocardia cor' was favoured. Van Voorthuysen (1954) also correlated the Coralline Crag with this zone. Laga (1972) and Cambridge (1977) believed the Coralline Crag should be correlated with the Luchtbal Sands which overlie the Kattendijk Sands (or'zone a Isocardia cor') around Antwerp. Andrew and West (1977) describe a Coralline Crag pollen assemblage from an augered borehole near Orford. They tentatively suggested a Brunssumian age for this deposit. The Brunssumian stage is also believed to be equivalent to the Luchtbal Sands (Laga 1972; Zagwijn and Staalduinen 1975). Wilkinson (1980) correlated the ostracods and foraminifers of the Coralline Crag with those of the Kattendijk and Luchtbal Sands. In Holland the Coralline Crag has been correlated with part of the Oosterhout Formation which in its lower part equates with the Luchtbal Sands of Belgium. Correlation with sequences in other more distant sedimentary basins is difficult. Reid (1890) and Burrows (1895a) correlated the Coralline Crag with the Plaisancian deposits of the Mediterranean; but Harmer (1900b) favoured correlation with the Astian of Italy. This latter correlation was also advocated by Baden-Powell (1953, 1955a and 1960) using species of Turritella, and supported by Wilkinson (1980), using ostracods.

3. POST-CORALLINE CRAGS

Introduction

The post-Coralline Crag deposits of East Anglia [early Pleistocene according to Boswell (1952), Mitchell *et al.* (1973); but see below for discussion] comprise up to 80m of sands, shelly sands and subordinate clays, which were laid down in a shallow marine environment near the western edge of the North Sea basin. The Pleistocene sequence on land in East Anglia is very thin compared to the 1000m-thick sequence present in the centre of the North Sea basin (McCave, Caston and Fannin 1977). Various means of classification have been applied to these diverse and complex deposits. It was early realised (Charlesworth 1835) that two main units could be recognised, the strongly iron-stained shelly sands of Essex and Suffolk, termed the Red Crag, and the more variable sands and clays of Suffolk and Norfolk, termed the Norwich Crag. Closer examination revealed the difficulty of defining these units precisely or of making sense of the faunal and sedimentary variation within them. The abundant and diverse molluscan fauna attracted a great deal of study in the middle and late 19th century and formed the basis for most classificatory schemes of that time. Bell and Bell (1872), Prestwich (1871b, 1871c), Wood (1848-1882) and Harmer (1914-1925) cited long faunal lists, but unfortunately few of these studies were quantitative, which considerably reduces their value. The decline in the number of extinct and southern (warm water) species from south to north in East Anglia was used to develop the concept of successive Crag deposits overlapping each other northwards. Harmer (1900a, 1902), in a synthesis that endured for over half a century, established a number of zones (see Funnell & West 1977) and stages (Fig. 4), each with a characteristic mollusc fauna and a limited geographical distribution.

This scheme, which represents essentially a progressive cooling trend, was superseded only when analyses of pollen and foraminifers, obtained by the drilling of boreholes through some of the thickest

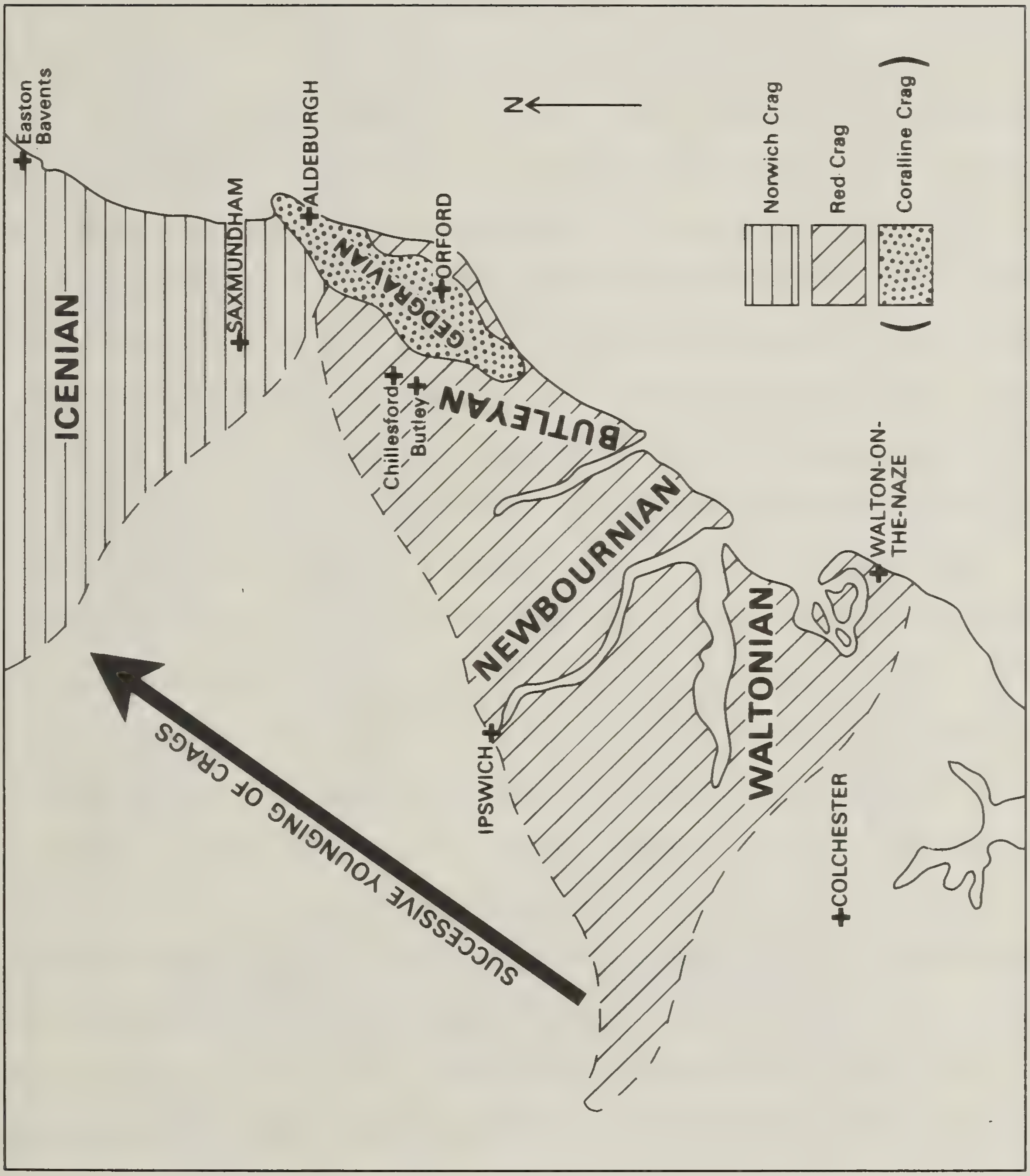
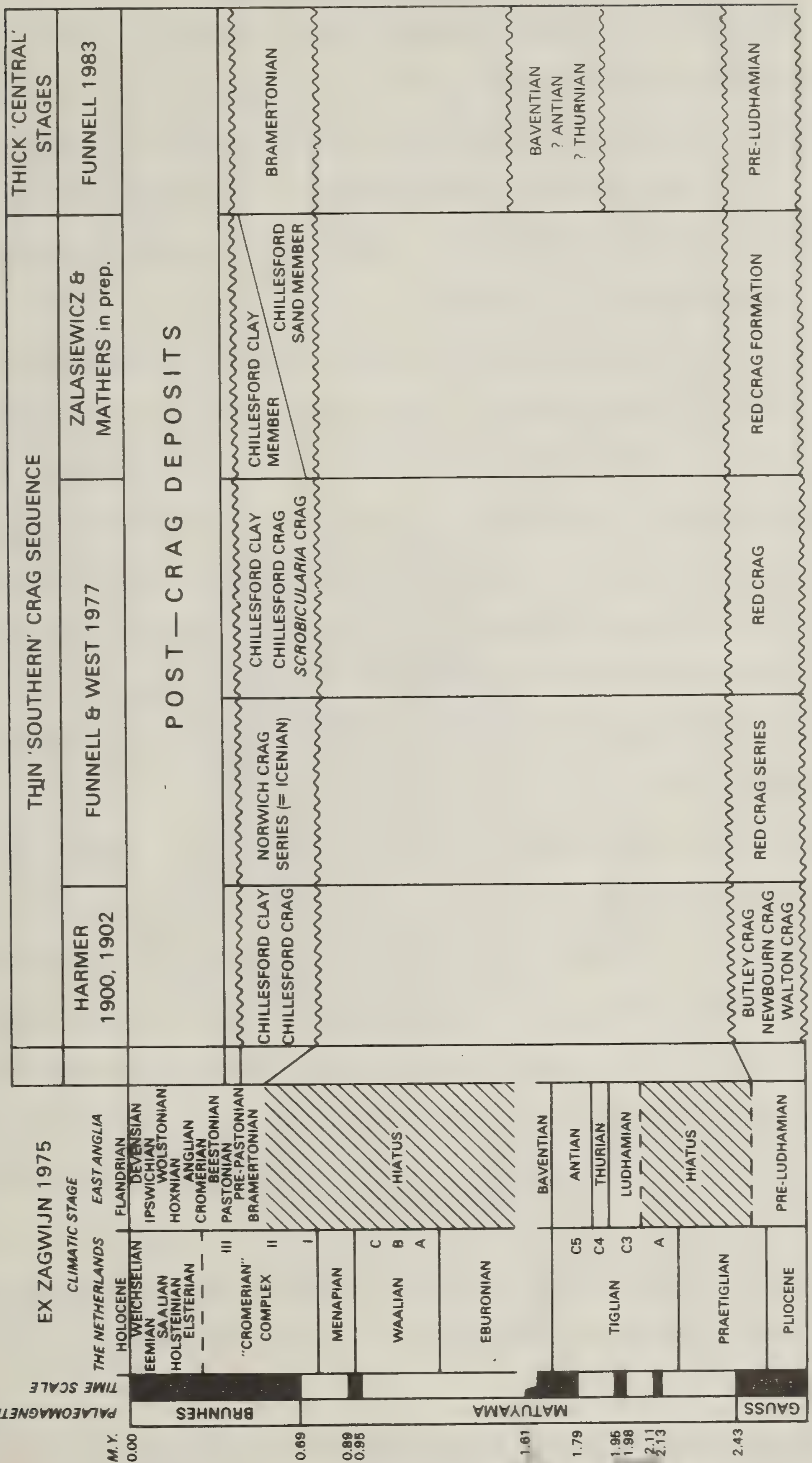

Easton Bavents
ALDEBURGH
SAXMUNDHAM
ORFORD
ICENIAN
GEDGRAVIAN
Chillesford
Butley
BUTLEYAN
NEWBOURNIAN
WALTON-ON-THE-NAZE
WALTONIAN
IPSWICH
COLCHESTER
SUCCESSIVE YOUNGING OF CRAGS
N
Norwich Crag
Red Crag
Coralline Crag

Fig. 4 Distribution of the Red Crag 'stages' after Harmer (1902)

Crag sequences (in particular those at Ludham and Stradbroke) revealed the presence of several climatic cycles within the Crag sediments (West 1961; Funnell 1961; Beck, Funnell and Lord 1972). Climatic oscillations inferred from pollen spectra were subsequently adopted as the best practicable chronostratigraphic basis for zonation in the Quaternary of Britain (West 1963; Mitchell et al. 1973). The identification and correlation of the Quaternary climatic episodes that have been recognised in the complete sequences obtained from certain parts of the ocean floor (Shackleton 1977) is difficult in the higher energy marginal marine Crag sediments. Gaps in the sedimentary record, coupled with reworking, abrasion and oxidation of some of the fossils present formidable problems, although these are gradually being resolved as more evidence accumulates.

The inclusion of these deposits within the Pleistocene corresponds to the 'classical' British position adopted by Boswell (1952) and Mitchell et al. (1973), in which the base of the Pleistocene is taken at the base of the 'Walton' Red Crag. It is likely however that the lower part of the post-Coralline Crag deposits may again be formally assigned to the Pliocene, but this will have to await the satisfactory resolution of the position of the Plio-Pleistocene boundary outside Britain. The normally magnetised Pre-Ludhamian sediments of the Stradbroke borehole have been correlated with the normally magnetised sediments below the Gauss/Matuyama polarity reversal (2.41 Ma) in the Netherlands (Fig. 5; Curry et al. 1978). The Gauss/Matuyama boundary is thought to correlate approximately with the floral deterioration at the base of the Reuverian, which has been adopted as the base of the Pleistocene in the North Sea basin (Curry et al. 1978). Alternatively, the

South-East Suffolk


THICK 'CENTRAL' STAGES
FUNNELL 1983
THIN 'SOUTHERN' CRAG SEQUENCE
ZALASIEWICZ & MATHERS in prep.
FUNNELL & WEST 1977
HARMER 1900, 1902
EX ZAGWIJN 1975
CLIMATIC STAGE
THE NETHERLANDS
EAST ANGLIA
TIME SCALE
PALAEOMAGNETIC POLARITY
M.Y.
POST—CRAG DEPOSITS
BRAMERTONIAN
BAVENTIAN
? ANTIAN
? THURNIAN
PRE-LUDHAMIAN
CHILLESFORD CLAY MEMBER
CHILLESFORD SAND MEMBER
RED CRAG FORMATION
CHILLESFORD CLAY
CHILLESFORD CRAG
SCROBICULARIA CRAG
RED CRAG
NORWICH CRAG SERIES (= ICENIAN)
RED CRAG SERIES
CHILLESFORD CLAY
CHILLESFORD CRAG
BUTLEY CRAG
NEWBOURN CRAG
WALTON CRAG
HOLOCENE
WEICHSELIAN
EEMIAN
SAALIAN
HOLSTEINIAN
ELSTERIAN
"CROMERIAN" COMPLEX
III
II
I
MENAPIAN
WAALIAN
C
B
A
EBURONIAN
TIGLIAN
C5
C4
C3
A
PRAETIGLIAN
PLIOCENE
FLANDRIAN
DEVENSIAN
IPSWICHIAN
WOLSTONIAN
HOXNIAN
ANGLIAN
CROMERIAN
BEESTONIAN
PASTONIAN
PRE-PASTONIAN
BRAMERTONIAN
HIATUS
BAVENTIAN
ANTIAN
THURIAN
LUDHAMIAN
HIATUS
PRE-LUDHAMIAN
BRUNHES
MATUYAMA
GAUSS
0.00
0.69
0.89
0.95
1.61
1.79
1.96
1.98
2.11
2.13
2.43

ig. 5 Correlation of the Crag deposits of south-east Suffolk [correlation with the Netherlands modified after Zagwijn (1975)]

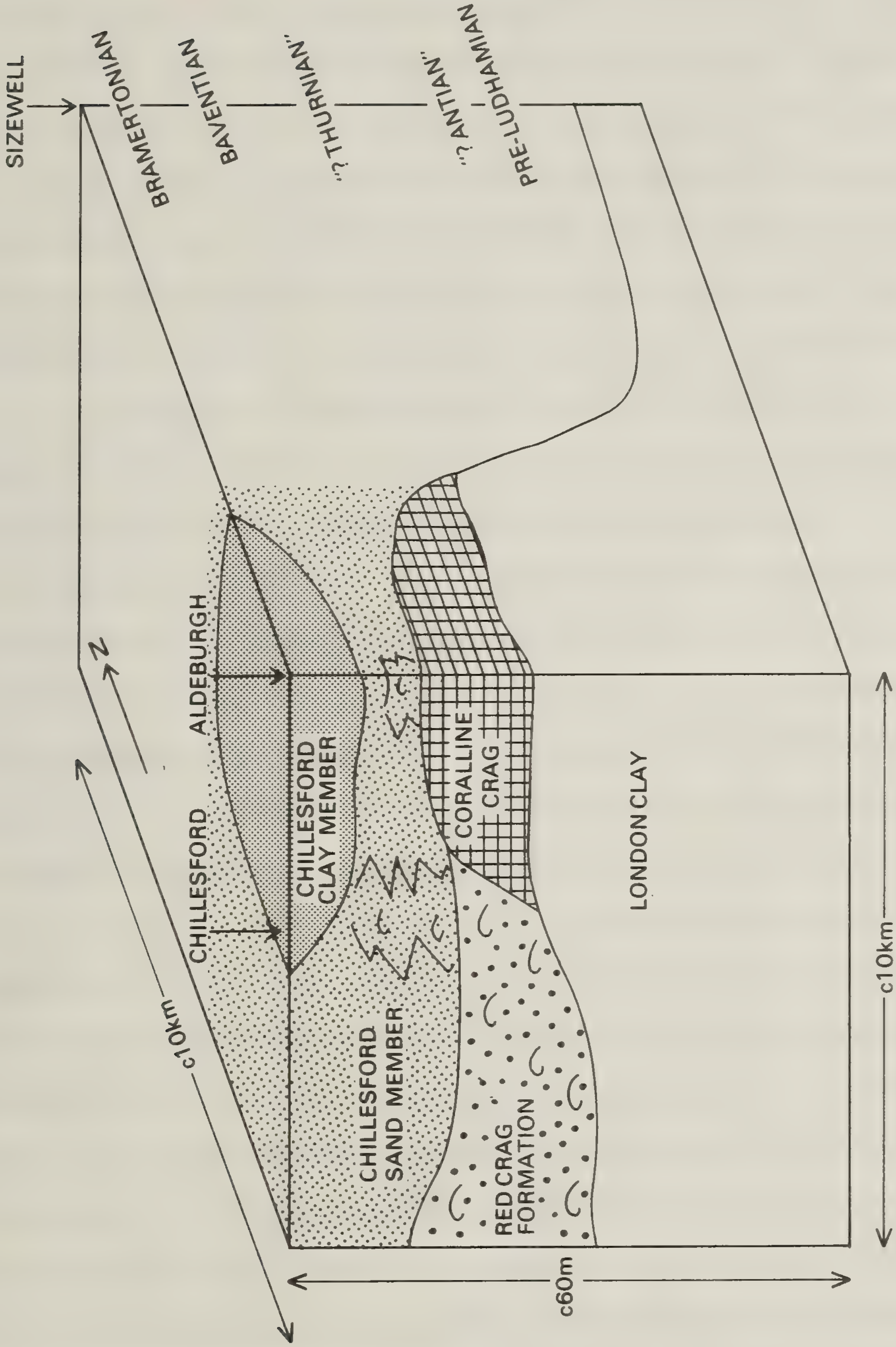
Stradbroke Pre-Ludhamian may be younger (Beck, Funnell & Lord 1972), and correlate with the normally magnetised sediments of the Olduvai (Gilsa) event (1.79-1.61 Ma); the end of the Olduvai event appears to correspond to the base of the Pleistocene, as established since 1948 in the international type section of the Plio-Pleistocene boundary at Calabria, Italy (Curry et al. 1978).

The following description of the Crags in south-east Suffolk uses the terms 'Red Crag' and 'Norwich Crag' since this is the accepted nomenclature and has been recently reassessed (Funnell and West 1977). A lithostratigraphy, independent of any palaeontological bias is currently being erected (Zalasiewicz and Mathers, in prep.) though at present it can be applied only to the area round Aldeburgh, Chillesford and Orford. Wherever possible, cross reference is made in the following description to this lithostratigraphy, as well as to the standard chronostratigraphic stage system.

Two main types of sequence can be recognised. South of the Aldeburgh-Gedgrave Coralline Crag ridge there is a relatively attenuated sequence of Red Crag (Fig. 6). In terms of the standard chronostratigraphy only the "Pre-Ludhamian" and the much younger Bramertonian stages have been recognised on this ridge or to the south. North of Aldeburgh the sequence thickens (Fig. 6) and there is evidence of the intervening "Thurnian", "Antian" and Baventian stages (Fig. 6). (When stage names are given in quotation marks they have not been identified on the basis of the defining pollen assemblages but on some complementary criterion, e.g. foraminifer assemblages.)

3a. **RED CRAG**

South-east Suffolk includes most of the surface outcrop of the poorly sorted iron-stained shelly sands referred to as the Red Crag.


SIZEWELL
BRAMERTONIAN
BAVENTIAN
"? THURNIAN"
"? ANTIAN"
PRE-LUDHAMIAN
N
ALDEBURGH
CHILLESFORD
CHILLESFORD CLAY MEMBER
CHILLESFORD SAND MEMBER
CORALLINE CRAG
RED CRAG FORMATION
LONDON CLAY
c10km
c10km
c60m

ig. 6 Schematic diagram of the Crag deposits of the area around Chillesford, Aldeburgh and Sizewell. Lithostratigraphy from Zalasiewicz & Mathers (in prep.); biostratigraphical stages at Sizewell after Funnell (1983)

Though the original definition (Charlesworth 1835) was based largely in terms of physical properties the term has come to be used chiefly to indicate a suite of mollusc assemblages (e.g. Harmer 1900a, Cambridge 1977). A Red Crag Formation was included as part of a comprehensive lithostratigraphical classification of the early Pleistocene deposits of East Anglia (Funnell and West 1977) and this name has been applied to a distinct lithostratigraphical unit recognised during recent British Geological Survey mapping in the Aldeburgh-Orford area (Zalasiewicz and Mathers, in prep.).

Lithology and Sedimentary structures. A coarse lag gravel occurs in pockets at the base of the Red Crag, and contains phosphatic nodules (largely reworked from the London Clay, and once an important source of fertilizer), vertebrate remains, and "box-stones", (fragments of brown sandstone some of which contain moulds of Miocene fossils).

Large-scale tabular cross-sets up to 4m high are characteristic of the lower part of these deposits, together with a variety of small-scale sedimentary structures including trough cross-sets, ripples and horizontal, planar bedding.

Burrowed horizons are common in the upper parts of the deposit where the sediments are predominantly horizontally planar bedded. This upward change in the sedimentary style of the deposits is interpreted by Dixon (1979) in terms of shallowing of water prior to the cessation of sedimentation in the Red Crag basin. The sequence as a whole is regarded by Boatman (1976) and Dixon (1979) as being deposited in a shallow, tidally dominated, marine regime.

Molluscs. Harmer's "stages" of the Red Crag are now thought to be geographically restricted biofacies (Funnell and West 1977); their use in this context is still retained (e.g. Cambridge 1977). Some recent modern ecological interpretations of Crag molluscs (Dixon 1977) emphasise the close relationship of the fauna and sedimentary environment, and the climatic interpretations of the earlier authors are heavily qualified. However, the overlap of a high Boreal and low Boreal epifauna throughout the Red Crag has, by comparison with the present-day Northern Irish coast, been taken to indicate summer water temperatures of 13°-15°C and winter water temperatures of 6°-8°C (Dixon 1977); an increase in the gastropod *Buccinum undatum* in the upper part of the Red Crag may suggest cooling (Dixon 1977).

Foraminifera. Although the systematic study of Crag foraminifers has almost as long a history as that of the molluscs (e.g. Jones, Parker and Brady 1866; Burrows 1895a, 1895b), the usefulness of these microfossils in determining past environmental conditons of the Crag deposits was fully realised only relatively recently, in large part through the investigations of material from the Ludham (Funnell 1961) and Stradbroke (Beck, Funnell & Lord 1972) boreholes. Quantitative analysis of the foraminifers of the Red Crag (Funnell 1961; Beck, Funnell & Lord 1972; Funnell & West 1977) showed that at Walton-on-Naze, the type locality for the 'Waltonian' stage of Harmer (1900a), the assemblage has Lusitanian (warm water/southern) affinities, and in characterised by an abundance of *Pararotalia serrata*, together with *Elphidium haagensis* unaccompanied by *E. frigidum*. The Red Crag of the Neutral Farm, Butley section, the type locality for the 'Butleyan' stage of Harmer (1900a), shows evidence of increasing Boreal (cool water/northern) influence, as *E. frigidum* has increased in numbers while *P. serrata* and *E. haagensis* are much reduced or absent. This trend, reflecting a progression from warm to cool conditions, has been correlated with a similar trend observed in the basal 25m of the

Stradbroke borehole, the type section of the Pre-Ludhamian stage (Beck, Funnell and Lord 1972).

In the thicker Crag sequence north of Aldeburgh, a "Pre-Ludhamian" fauna has been obtained from below -35m O.D. in a borehole at Sizewell (Funnell 1983); E. frigidum is absent from this material.

Pollen. No pollen has yet been obtained from any surface exposure of the coarse-grained, oxidised Red Crag sediments. Pollen from the type Pre-Ludhamian of the Stradbroke borehole is dominated by Pinus (pine) associated with Betula (birch) and Alnus (alder). It indicates the regional presence of coniferous woodland of a cool temperate type.

The only palynological evidence of the Pre-Ludhamian stage in the area covered by this account herein comes from the thick Crag sequence north of Aldeburgh, as seen in borehole material from Sizewell. Here a flora with very high frequencies of Pinus, indicative of coniferous woodland in a cool temperate climate, was present at between -36m O.D. and -37m O.D. (West and Norton 1974).

3b. **NORWICH CRAG**

The type locality of the Norwich or 'Icenian' Crag is at Bramerton, Norfolk. The unit is characterised by the presence of a somewhat greater proportion of "northern" molluscs (Harmer 1900, 1902) than the Red Crag. Widespread in Norfolk, it has been shown as extending southwards into south-east Suffolk to a varying extent (Fig. 1; Harmer 1902 p.432; West and Norton 1974, p.2). In south-east Suffolk the most distinctive lithological member within these beds is the Chillesford Clay, which was originally mapped during the Geological Survey of Great Britain (1883).

The recognition of 'Norwich Crag' in the area south of Aldeburgh is based on the presence of both macro and microfossils in a few outcrops of shelly beds, notably the Chillesford Church Pit section. These beds either directly overlie the Red Crag, as at Chillesford, or rest unconformably on Coralline Crag. Part, or all, of these deposits have been termed the Chillesford Crag, Chillesford Beds, Chillesford Sand or *Scrobicularia* Crag by various authors. Recent BGS mapping of the Aldeburgh-Orford area has shown that these isolated shelly pockets lie within an extensive mappable unit of largely unfossiliferous fine-grained sand; this has been termed the Chillesford Sand Member Zalasiewicz and Mathers in prep.), re-invoking a classification put forward initially by Prestwich (1871a, b, c). The Chillesford Clay Member is a lateral equivalent of the upper part of the Chillesford Sand Member.

Lithology and sedimentary structures. The Chillesford Sand Member of the Aldeburgh-Orford area is typically a fine-grained well-sorted sand up to 15m thick (Zalasiewicz and Mathers, in prep.). Sedimentary structures, where present, include ripple lamination, horizontal bedding, and burrows, with some medium-scale cross-bedding towards the base of the unit. The fossiliferous section at Chillesford Church Pit epresents a local facies variant, and shows poorly-sorted sands and ilty sands, interbedded with medium to coarse shelly sand towards the ase of the section. There is no obvious visible unconformity at the junction of these beds and the underlying Red Crag.

The Chillesford Clay is generally a brown grey unfossiliferous or parsely fossiliferous clay which includes sand laminae in places.

ollusca. South of Aldeburgh, this fauna is largely known from the hillesford Church Pit locality, where a limited abraded fauna from he '*Scrobicularia* Crag' shows evidence of upwards shallowing ublittoral to intertidal conditions. A decrease in palaeotemperature from boreal to subarctic/high boreal in the upper part of the sequence was inferred from the replacement of *Spisula* and *Corbula* by *Yoldia myalis* (West and Norton 1974). A very limited fauna from the Chillesford Clay was described by Prestwich (1849), but this has not been reinterpreted in modern terms.

From Aldeburgh northwards, 'Icenian' molluscan assemblages become more common, including faunas recently described from subsurface exposures at Aldeburgh, Thorpe Aldringham and Sizewell, (West and Norton 1974). These indicate shallow water conditions, including sheltered, reduced-salinity tidal flat conditions. The palaeotemperatures indicated by the mollusca are similar to those of modern boreal seas.

Foraminifera. A fauna from the upper part of the 'Chillesford Crag' of the Chillesford Church Pit has been listed by Funnell (1961). The restricted and specialised fauna is dominated by *Ammonia beccarii* (recorded as *'Rotalia' beccarii*), which indicates a tidal-flat or lagoonal environment, with temperatures not dissimilar to the present day. It has been correlated with the Bramertonian Stage (Funnell, Norton and West 1979). No foraminifers have been described from the Chillesford Clay.

The thicker central Crag sequence north of the Aldeburgh-Gedgrave Coralline Crag ridge shows evidence of a more complete Pleistocene sequence. A "Bramertonian" assemblage, dominated by *Elphidiella hannai*, was present near the top of the Sizewell borehole sequence (Funnell 1983). Between that assemblage and the "Pre-Ludhamian" assemblage near the base of the borehole (noted above) the following sequence was described by Funnell (1983):

iii. Between -3.6m O.D. and -18.4m O.D., a relatively cold water assemblage containing Elphidium orbiculare, E. frigidum and E. excavatum has been correlated with the Baventian.

ii Between -18.4m O.D. and c.-35m O.D., a temperate assemblage, very similar to the Bramertonian assemblage at the top of the borehole has been tentatively assigned to the Antian stage.

i. In a thin layer at -35.0m O.D., immediately overlying the "Pre-Ludhamian" part of the borehole, a species-poor assemblage with Elphidiella hannai highly dominant, indicates Arctic conditions, and perhaps represents the Thurnian stage.

Pollen. A 'Chillesford pollen assemblage'was obtained from thin silty clay laminae in the 'Scrobicularia Crag' of West and Norton (1974) (= the base of the 'Chillesford Crag' of Funnell 1961) of the Chillesford Church Pit, and also from the Aldeburgh Brickworks Pit (West and Norton 1974). High frequencies of arboreal pollen, with Ulmus (elm), Quercus (oak), Alnus (alder) Carpinus (ash), Pinus (pine), Picea (spruce) and Betula (birch) all well represented, indicate the regional presence of a largely deciduous temperate forest. Initially tentatively assigned to the Pastonian Stage (West and Norton 1974) the assemblage was subsequently linked to the preceding Bramertonian temperate stage (Funnell, Norton and West 1979).

A 'Chillesford pollen assemblage' was also obtained from levels of +3.0 to +4.5m O.D. in trenches at Sizewell. At -8.5m O.D., in a borehole at Sizewell, an assemblage with much higher frequencies of non-arboreal pollen and a near-absence of thermophilous tree genera was correlated with the Baventian cold stage (West and Norton 1974). No pollen was found, however, that would support the tentative identifications of the Thurnian and Antian stages, as indicated by the foraminiferal assemblages.

4. KESGRAVE SANDS AND GRAVELS

Overlying the Pleistocene 'Crags' of south-east Suffolk are a suite of sand and gravel deposits referred to by Rose and Allen (1977) and Rose, Allen and Hey (1976) as the Kesgrave Sands and Gravels. These deposits occur beneath glacial deposits in the north-west of the area, and form broad low-lying plateaux, possibly relict braidplains, towards the coast where the glacial deposits are largely absent. The Kesgrave Sands and Gravels are commonly five to ten metres thick and are believed to represent the deposits of an extensive braided river system which flowed north-eastwards across Suffolk from the London Basin. The distinction between these deposits and the Anglian Barham Sands and Gravels of Rose and Allen (1977) is made difficult by fluvial reworking, which has led to similar clast compositions; the two can be readily distinguished only where the latter deposits contain chalk. However, many of the sand and gravel deposits occur as thin surficial spreads which are prone to decalcification, so that the distribution of the two deposits not known in detail. The glacial sands and gravels (Barham Sands and Gravels) are however believed to be of restricted extent, and it is likely that most of the widespread coastal outcrops previously mapped as 'Glacial Sands and Gravels' are Kesgrave Sands and Gravels.

Exposures in pits reveal a widespread rubified horizon on the upper surface of the deposit. This is interpreted as a temperate *sol lessive*, whose structure is overprinted by cold phase structures including cryoturbation associated with the Anglian glaciation. This soil horizon is regarded as Cromerian in age and the Kesgrave Sands and Gravels are assigned by Rose and Allen (1977) to the Beestonian. This stratigraphy has been questioned by Lake, Ellison and Moorlock (1977), and a possible Pastonian age for the soil horizon and Pre-Pastonian age for the sands and gravels implied by Hey (1982). The widespread occurrence of the deposits and the range of heights at which they occur over parts of East Anglia suggest a prolonged and complex history which may well occupy more than one stage of Pleistocene time.

5. ANGLIAN GLACIATION

The deposits produced by the Anglian glaciation are widespread in south-east Suffolk. In the north-west of the area much of the ground is covered by a thick sheet of chalky boulder clay (Lowestoft Till). Traced south-eastwards towards the coast, the till sheet thins and is absent beyond a line approximately linking Ipswich-Woodbridge and Leiston. This is partly because of the deeper dissection and more widespread erosion of the coastal area, although the thinning is thought to be partly original. The presence of isolated patches of till and other glacial sediments well away from the main till sheet argues strongly, however, for ice over the whole area, with substantial post-Anglian erosion. The widespread erosion in the coastal belt and the absence of any landforms or deposits characteristic of many ice-margins makes the maximum extent of the ice-sheet difficult to locate precisely.

Thin sequences of till associated with glaciofluvial and glaciolacustrine deposits are banked against the sides and on the floors of several of the major valleys, including the Alde and Butley Rivers, which were thus cut before the deglaciation of the Anglian ice-sheet. Regionally the drainage of the Anglian ice-sheet seems to have taken place through a network of large buried tunnel-valleys (Boswell 1914; Woodland 1970). Woodland (1970) gives an account of one such tunnel valley cut into the Chalk beneath Ipswich. On a smaller scale, a series of subglacial channels have been recognised from the Aldeburgh Area (Mathers and Zalasiewicz in prep.).

6. IPSWICHIAN INTERGLACIAL

The type section of the Ipswichian interglacial is located at Bobbitshole, south of Ipswich (West 1957), where several metres of fresh-water silts and clays fill a solution hollow in the Chalk (Lake pers. comm.). The pollen from the site is considered by West (1957) to be similar to that of the Eemian Interglacial of continental Europe. A late Ipswichian fluvial deposit (brickearth) has been described from the foreshore at Stutton on the Stour Estuary, south of Ipswich (Sparks and West 1963).

7. FLANDRIAN

Extensive Flandrian deposits occur near Orford Ness. The deposits occur as a series of embayments into the Crag outcrop, and are backed by a pre-Flandrian degraded cliff line. The Flandrian deposits rest on Crags and London Clay, into which marine planation surfaces have been cut (Carr and Baker 1968). The deposits are locally thicker than ten metres and are clays and silts with subordinate sands and peats. Near the Orford Ness shingle ridge some of the more recent deposits interdigitate with coarse gravels associated with the spit. Most of the deposits are believed to have formed on estuarine mud-flats and salt-marshes and represent aggradation in response to rising sea levels in Flandrian times. A peat layer close to the base of the Holocene succession on Aldeburgh marshes has been dated at 8,640 ± 145 and 8,460 ± 145 B.P., giving an estimate of the onset of deposition in this area. The growth of the Orford Ness Spit in historical times is traced in several papers by Steers (1926) and Carr (1969, 1970, 1972).

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THE GLACIAL GEOLOGY OF NORFOLK

G.S.Boulton*, F.Cox+, J.Hart* and M.Thornton+

1. INTRODUCTION

The ice age in Norfolk left a legacy of varied and spectacular geology, but because of the richness of the evidence Norfolk not only makes a major contribution to our knowledge of Ice Age Britain but it also generates many enigmas. For instance the magnificent exposures in the north-eastern coastal cliffs have tempted us to develop a more sophisticated stratigraphy than in many other poorly exposed areas where the evidence which might invalidate our generalisations is conveniently hidden. Thus, rather than attempt to elucidate many of the controversial details of stratigraphical correlation we have tried to sketch the broad and most obvious outlines of Norfolk's glacial geology.

The developing British stratigraphical framework within which the Ice Age history of Norfolk is conventionally placed is shown in Table 1 together with postulated European equivalents.

2. CHARACTER, DISTRIBUTION AND STRATIGRAPHY OF THE GLACIAL SEDIMENTS

A major regional division between two lithologically distinct glacial sediments occurs across a line, shown in Figure 2, running along the Yare from Yarmouth to Norwich and from Norwich to Weybourne. Outside this line there occur tills to which the term "Chalky Boulder Clays" has been applied, whilst inside the line occur tills known as "North Sea Drifts", and "Marly Drifts". Although these have been and

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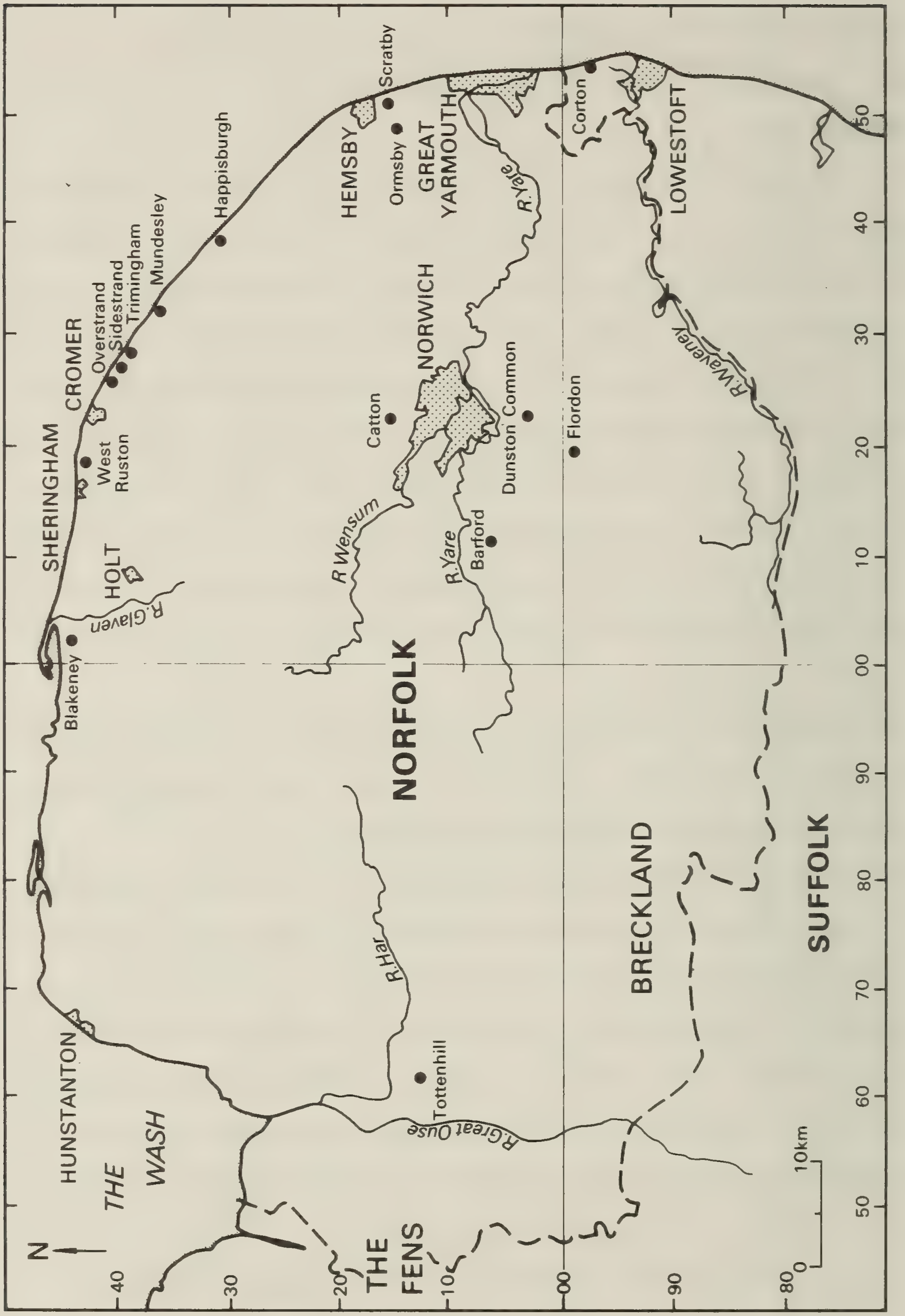
N
HUNSTANTON
THE WASH
THE FENS
SHERINGHAM
CROMER
HOLT
R.Glaven
Blakeney
West Ruston
Overstrand
Sidestrand
Trimingham
Mundesley
Happisburgh
HEMSBY
Scratby
Ormsby
GREAT YARMOUTH
NORWICH
Catton
R Wensum
R.Yare
Barford
Dunston Common
Flordon
Corton
LOWESTOFT
R.Waveney
NORFOLK
R.Har
Tottenhill
R.Great Ouse
BRECKLAND
SUFFOLK
10km
0
40
30
20
10
00
90
80
50
60
70

Figure 1. - Sketch map of Norfolk showing place names referred to in text. The border grid corresponds to National Grid 10km divisions.

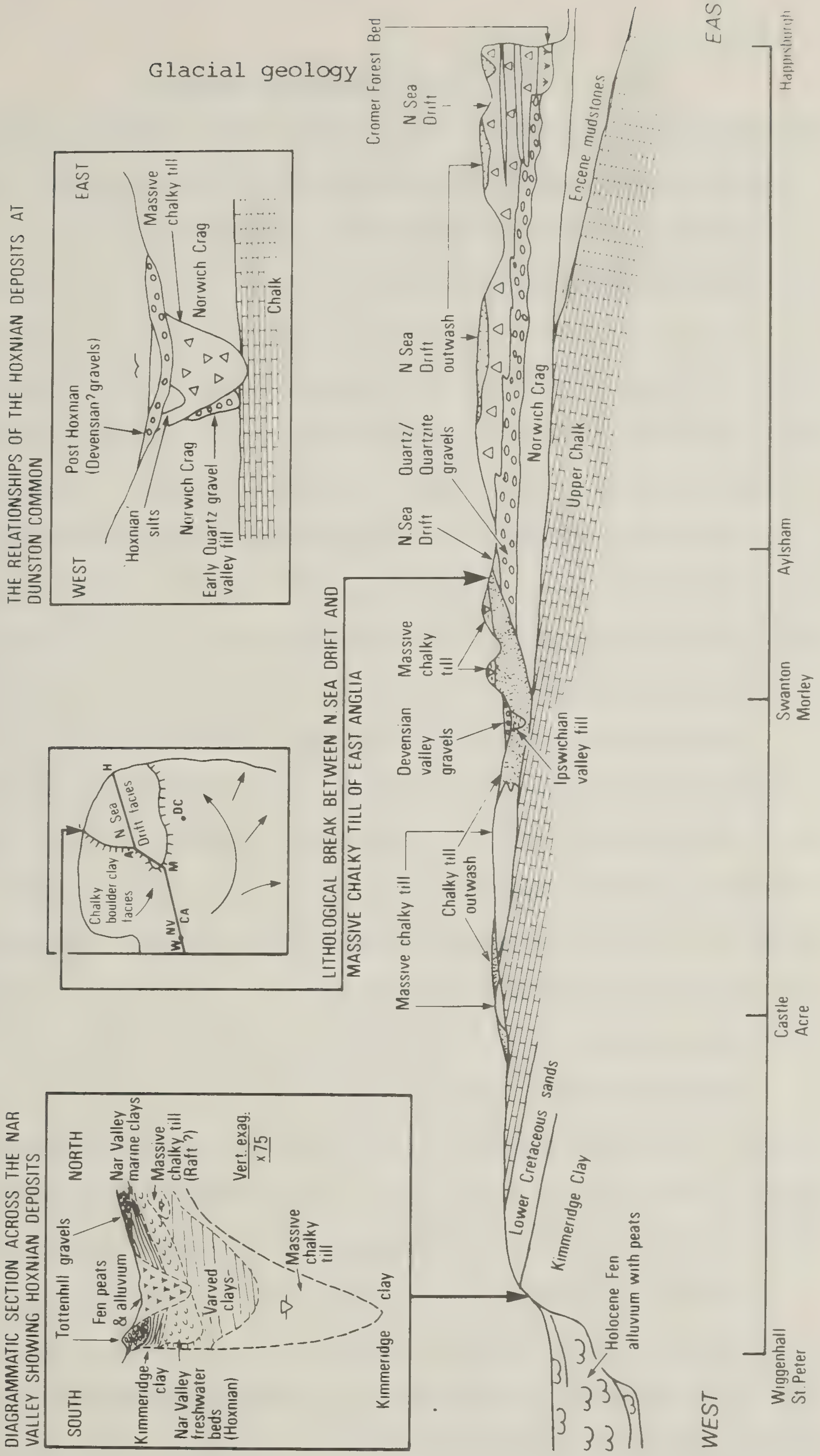
DIAGRAMMATIC SECTION ACROSS THE NAR VALLEY SHOWING HOXNIAN DEPOSITS
SOUTH
NORTH
Tottenhill gravels
Fen peats & alluvium
Nar Valley marine clays
Massive chalky till (Raft ?)
Vert. exag. x 75
Kimmeridge clay
Nar Valley freshwater beds (Hoxnian)
Varved clays
Massive chalky till
Kimmeridge clay
Chalky boulder clay facies
N Sea Drift facies
W
NV
CA
M
A
DC
H
THE RELATIONSHIPS OF THE HOXNIAN DEPOSITS AT DUNSTON COMMON
WEST
EAST
Post Hoxnian (Devensian? gravels)
'Hoxnian' silts
Norwich Crag
Early Quartz gravel valley fill
Massive chalky till
Norwich Crag
Chalk
LITHOLOGICAL BREAK BETWEEN N.SEA DRIFT AND MASSIVE CHALKY TILL OF EAST ANGLIA
Cromer Forest Bed
N Sea Drift
N Sea Drift outwash
Quartz/ Quartzite gravels
N.Sea Drift
Massive chalky till
Devensian valley gravels
Massive chalky till
Chalky till outwash
Massive chalky till
Eocene mudstones
Norwich Crag
Upper Chalk
Ipswichian valley fill
Lower Cretaceous sands
Kimmeridge Clay
Holocene Fen alluvium with peats
WEST
EAST
Wiggenhall St Peter
Castle Acre
Swanton Morley
Aylsham
Happisburgh

Figure 2. - Schematic east-west cross-section across the Norfolk drifts with inset map showing the distribution at surface of the two principal facies.

are used as stratigraphic terms, it is safer at the moment to use the terms to describe lithofacies rather than to assume that lithological similarity implies stratigraphical equivalence.

2a. "Chalky Boulder Clay"

This has a clay-rich matrix, much of which is probably derived from the Kimmeridge Clay. The dominant clasts are of chalk and flint with Jurassic limestones and Bunter quartzites as common minor constituents, together with rare igneous rocks. Within a single stratigraphical unit this "Chalky Boulder Clay" facies may change its character as the source rocks change, becoming locally very sandy or dominated by reconstituted chalk.

2b. "North Sea Drift"

This is best seen in the dramatic coastal cliffs of north-east Norfolk. It is a sandy, silty till facies. Often highly laminated it commonly contains beds or discrete lenses of sand. Clasts are relatively rare compared with the "Chalky Boulder Clay", and are dominantly flint with rare igneous and metamorphic erratics. Locally this facies has been called the Cromer Till and Norwich Brickearth.

2c. "Marly Drift"

A third lithofacies, the so-called Marly Drift (Straw, 1979; Perrin, Davies and Fysh, 1973) is found in north Norfolk. This is a highly laminated diamicton, much like the North Sea Drift, except that its dominant laminae are of crushed and reconstituted chalk.

The obvious conclusion is that these lithofacies simply reflect different sources of supply. The first, the Jurassic lowlands around the Fenland basin and the Chalk of west and central Norfolk; the second and third, the Chalk of north-east Norfolk, whilst all three contain various materials (sands, clays, organic materials) from the various lithofacies of the early Quaternary. This hypothesis is supported by the till fabric measurements of West and Donner (1956), the compositional studies of Perrin, Rose and Davies (1979) and the evidence from west Norfolk of erratic transport towards the south-east (Gallois, 1979).

Figure 2 shows a diagrammatic east-west transect through the glacial deposits of Norfolk. On the east coast, there are within the North Sea drift Facies as many as three till units separated by sediment which reflect sub-aerial conditions. Inland one till unit, the Chalky Boulder Clay Facies, extends to the west and south. The North Sea Drift/Marly Drift Facies occupies the north-east area of the county. Near Aylsham and at Scratby the Chalky Boulder Clay Facies overlies the North Sea Drift Facies. The simplest explanation of this and of the distribution shown in Figure 2 is that both facies were laid down penecontemporaneously by two lobes of the same ice sheet with the flow from the north-west, which brought Chalky Boulder Clay material, dominating the later stages (Bristow and Cox, 1972).

The increase in the number of till units to the east and south (Figs. 2 and 3) is most simply explained by assuming that this reflects marginal oscillations of an ice sheet with an overall flow towards the south-east.

3. STRATIGRAPHICAL INTERPRETATION

At no point in East Anglia have interglacial deposits been found between glaciogenic sediments.

The glacial deposits so far described have been ascribed to a single complex glacial stage known as the Anglian Stage (Table 1). Along the coast, glacial deposits are frequently found overlying deposits of the Cromerian interglacial, whereas at many places within the region, such as Hoxne, Barford and Dunston Common (Fig.2; West, 1956; Cox and Nickless, 1972; Phillips, 1976) they are overlain by organic deposits ascribed to the Hoxnian interglacial.

TABLE 1

Conventional Stratigraphical Scheme for the Quaternary Ice Ages in Britain and Europe. (after Mitchell *et al* 1973)

Postulated Age	Environment	British Stages	Postulated European Stages Equivalents
	Temperate	FLANDRIAN	HOLOCENE
10ka			
	Cold	DEVENSIAN	WEICHSELIAN
110ka			
	Temperate	IPSWICHIAN	EEMIAN
128ka			
	Cold	WOLSTONIAN	SAALIAN
195ka		Ilfordian Interglacial? cold phase	
	Temperate	HOXNIAN	HOLSTEINIAN
251ka			
	Cold	ANGLIAN	ELSTERIAN
297ka		Glaciations Unknown in Britain	
	Temperate	CROMERIAN	

The type section for the pre-Hoxnian, post-Cromerian, Anglian Glacial Stage is at Corton on the coast, just south of the Norfolk/Suffolk border (Mitchell *et al*. 1973), within the zone showing glacial fluctuations (Table 2).

The "Plateau Gravels" at the top of the sequence are distinctively quartz and quartzite rich but cannot be readily related to other lithologies in the area.

TABLE 2

Type sequence of the Anglian Glacial Stage - Corton

?Age uncertain	Plateau Gravels	- Quartz and quartzite rich.
	Pleasure Gardens Till	- Flow till (Banham, 1971)
	Oulton Beds	- Varved Clays (Banham, 1971)
Anglian	Lowestoft Till	- Chalky Boulder Clay Facies.
	Corton Beds	- Braided outwash stream deposits from North Sea Drift glacier (D.Bridge, P.Hopson, pers. comm.1984) Shelly fauna, periglacial flora (West and Wilson, 1968), ice wedge casts.
	North Sea Drift	- North Sea Drift Facies
Cromerian	Cromer Forest Bed Series.	

Farther north at Ormesby St Margaret (Fig.1) there are three units of North Sea Drift Facies separated by units of Corton Beds type, (outwash sands?), a similar sequence to that identified by Banham (in West, 1977) at Happisburgh (Table 3).

TABLE 3

Sequence at Happisburgh according to Banham (in West, 1977)

Wolstonian -	Valley Gravels and Sands	5m+
	Gimingham Sands	4m+
	Third Cromer Till	11m
Anglian	Mundesley Sands	9m
	Second Cromer Till	3m
	Intermediate Beds	6m
	First Cromer Till	4m
Cromerian -	Cromer Forest Bed Series	1+

Near Paston Cliff (Fig. 3) the nature of the glacial sequence exposed in the coastal cliffs changes dramatically. It becomes much thicker, especially in its upper part where very thick sand and gravel masses are developed. They overlie and penetrate, as a series of

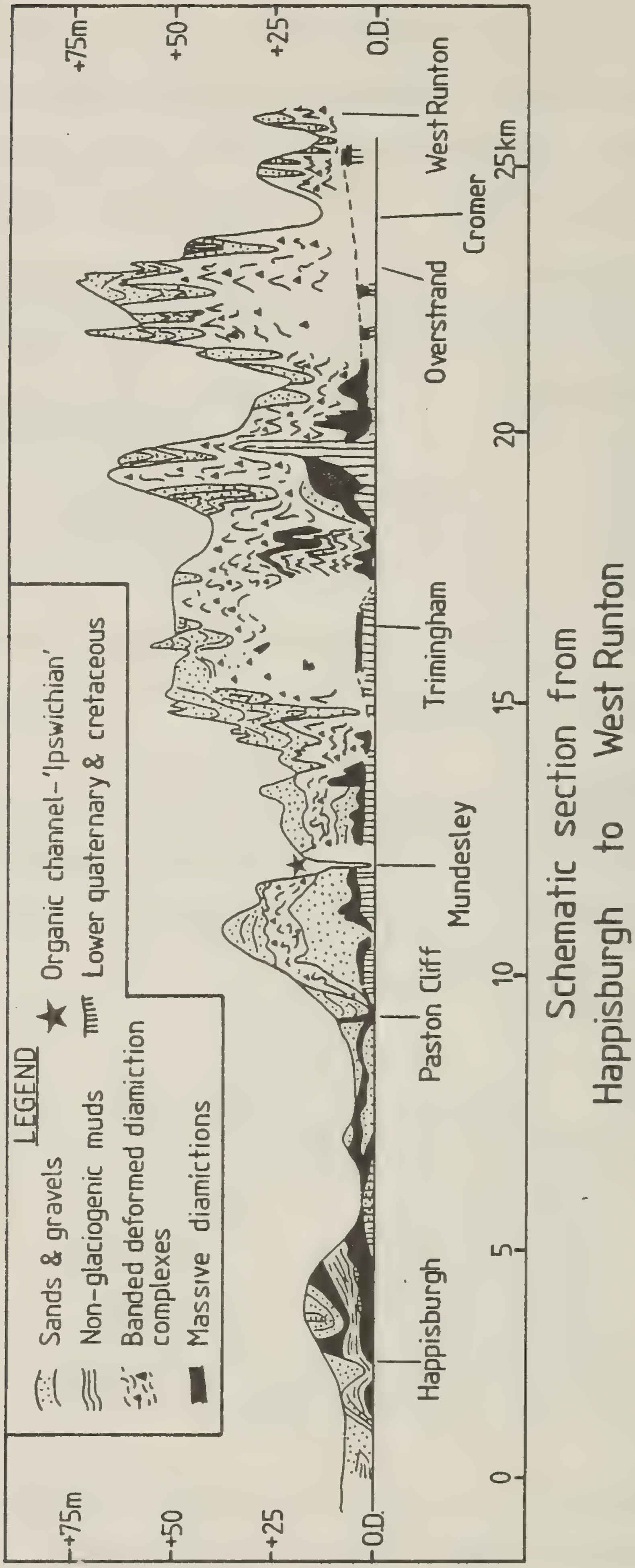
+75m
+50
+25
0.D.
West Runton
Cromer
Overstrand
Trimingham
Mundesley
Paston Cliff
Happisburgh
0
5
10
15
20
25km
LEGEND
Sands & gravels
Non-glaciogenic muds
Banded deformed diamiction complexes
Massive diamictions
Organic channel-'Ipswichian'
Lower quaternary & cretaceous
Schematic section from
Happisburgh to West Runton

Figure 3. - N.E. Norfolk coastal section from West Runton to Happisburgh. The continuation of the section to the north-west as far as Weybourne shows a similar sequence to that at West Runton except that the chalk bedrock platform rises above high tide level.

asins and pods, a complex sequence of diamicton units, which have een strongly deformed. These are the so-called "Contorted Drifts", hich occupy the upper part of the glacial sequence as far as undesley and Trimingham and the whole glacial sequence further north estwards to Weybourne. The till facies within them roughly falls ithin the definition of North Sea Drift and Marly Drift. Banham 1970) has attempted to trace a stratigraphy defined further south hrough this belt. This is clearly possible as far as just north of undesley and possibly just north of Trimingham. We feel that all pre-xisting post-Cromerian sediments have been completely re-worked by ater glacial tectonism and that from north of Trimingham to Weybourne he glacial sequence reflects only one or two episodes, of enecontemporaneous glacial deformation. Sections in this contorted elt, which demonstrate the style of deformation, are shown in Figure .

In the Nar Valley, Chalky Boulder Clay is overlain by varved lays which pass conformably up into sands and silts (Gallois, 1979) ith freshwater molluscs and pollen indicative of a warm temperate limate, thought by Stevens (1960) to represent the Hoxnian nterglacial. These in turn are overlain by clays and silts with rackish water bivalves suggesting a transgression to 20.23m above odern sea level (Stevens, 1960).

In the upper reaches of the Wensum Valley (Beetley, Swanton orley and Elsing) fossiliferous silts have been recognised as having distinctive temperate flora and fauna, which may be ascribed to the pswichian interglacial stage. The relationship of these silts to the oxnian interglacial is not obvious although most authors would

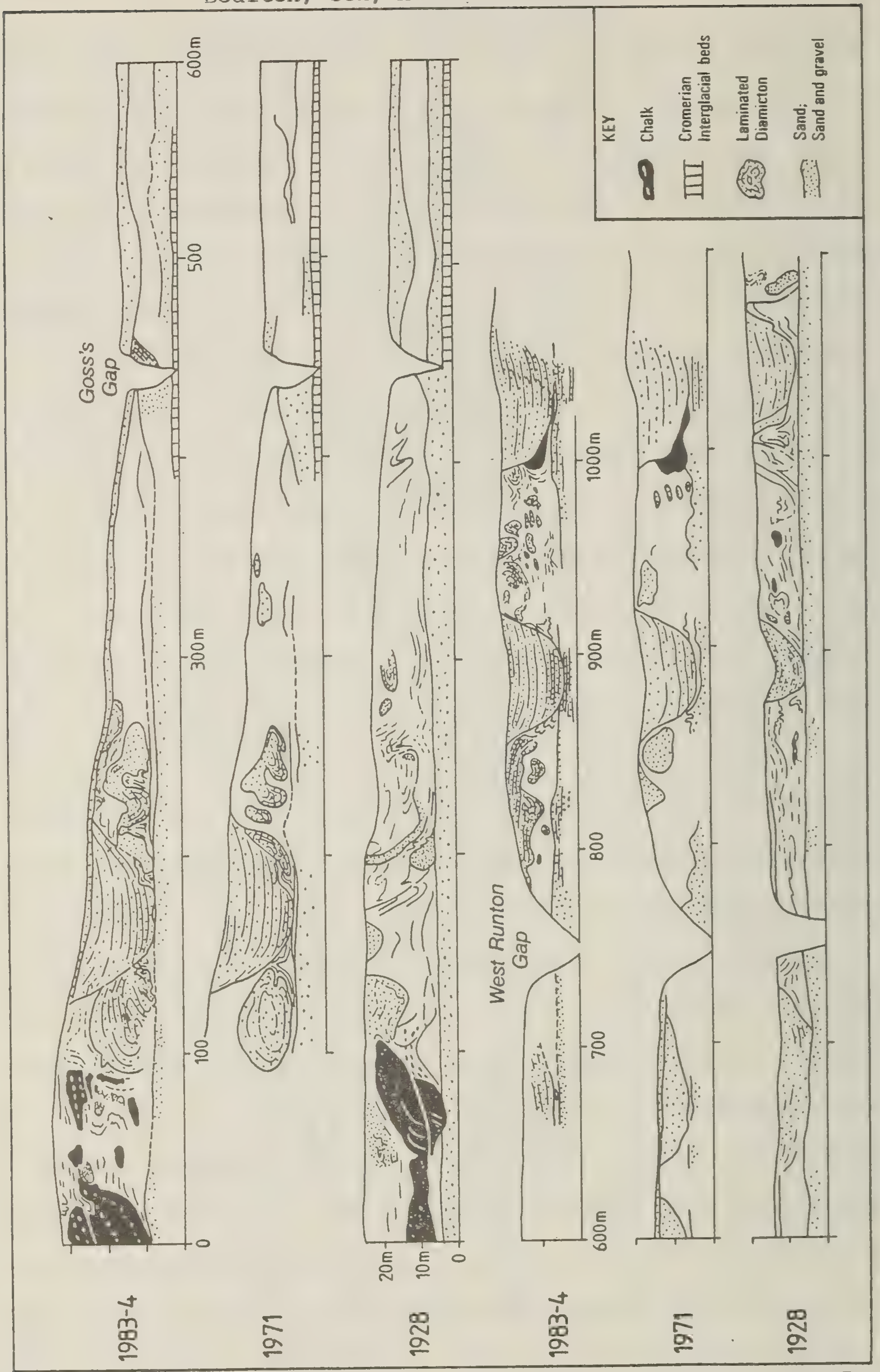
KEY
Chalk
Cromerian Interglacial beds
Laminated Diamicton
Sand; Sand and gravel
Goss's Gap
West Runton Gap
1983-4
1971
1928
1983-4
1971
1928
0
100
300m
500
600m
600m
700
800
900m
1000m
20m
10m
0

Figure 4. - The drift exposure in the vicinity of West Runton Gap, showing way in which coastal erosion reveals the three-dimensional structure. The 1928 section was compiled by Slater in an unpublished notebook.

support their separation by at least one intervening glacial stage (Wolstonian).

In the extreme north-west of Norfolk, a brown sandy till, known as the Hunstanton Till, was suggested by Suggate and West (1959) to be of Devensian (last glacial) age. Its gross lithological character and erratic content are demonstrably different from the Chalky Boulder Clay and the North Sea Drift. Straw (1960) and Madgett (1975) have stressed the similarity of this till and the soils developed on it with demonstrably Devensian tills and their soils in Holderness.

3. GLACIAL OUTWASH DEPOSITS

The largest and most impressive accumulation of ice marginal sediments on the east coast of England occurs in North Norfolk. From near Trimingham to north of Holt, a major sand and gravel ridge, the Cromer Ridge, occurs (Fig. 5). This is bounded on its north flank by a scarp which has all the appearances of an ice contact slope, complete with outwash plains to the south (Straw, 1979b) and numerous kame-like ridges and mounds and an undoubted esker south of Blakeney (Sparks and West, 1964). In a modern glacial environment such an assemblage would clearly indicate a long-term glacier standstill, either the maximum stage of an advance, or a major halt during retreat. Although Straw (1979) has argued that many of these features are erosional, it is difficult not to take the assemblage at its face value and draw the simple conclusion, particularly in view of the absence of signs of similar erosion in the nearby cliffs, that the assemblage reflects a major glacial halt stage.

It is clear that much of the Contorted Drift sequence as far as Trimingham, and possibly as far as Paston Cliff, lies on the proximal side of the Cromer Ridge and also that the major sand and gravel masses in the upper part of the sequence in this zone (Figs.3 and 4) belong to the Cromer Ridge outwash mass. Thus we conclude that the "Contorted Drifts" formed primarily during an advance to the Cromer Ridge or during a halt at this position during deglaciation.

A major belt of coarse gravel outwash sediments extends northwards from the western suburbs of Norwich in an apparently unbroken tract to the coast. These may be associated with outwash rivers flowing from an ice sheet lying along the Cromer Ridge, which produced hummocky supraglacial accumulations south of Holt (Fig.5). Although it is possible that this physical connection is coincidental and that more than one major glacial event may be involved. Detailed mapping will be necessary to resolve this problem. In the Norwich area these gravels have been related to the main Chalky Till facies of East Anglia (Cox and Nickless, 1972).

Thick sand and gravel units also occur in the Waveney Valley, comprising angular flints with minor quartz and quartzite pebbles. They form kame like masses along the valley margins and also underlie and interdigitate with the Chalky Boulder Clay Facies. Farther east they overlie North Sea Drift Facies (Fig. 2) reinforcing the conclusion that the ice that deposited the Chalky Boulder Clay was active after the North Sea Drift ice had decayed. The gravels prograde in an easterly direction and in the upper Wensum area they contain many locally derived large unweathered black flints. South of Norwich, angular and sub-angular gravels are more intimately related to till, and interdigitate with it.

In the eastern area occupied by North Sea Drift, quartz and quartzite rich gravels with a distinctive suite of volcanic rocks including felsites and rhyolites lie beneath the till. Hey (1980) has

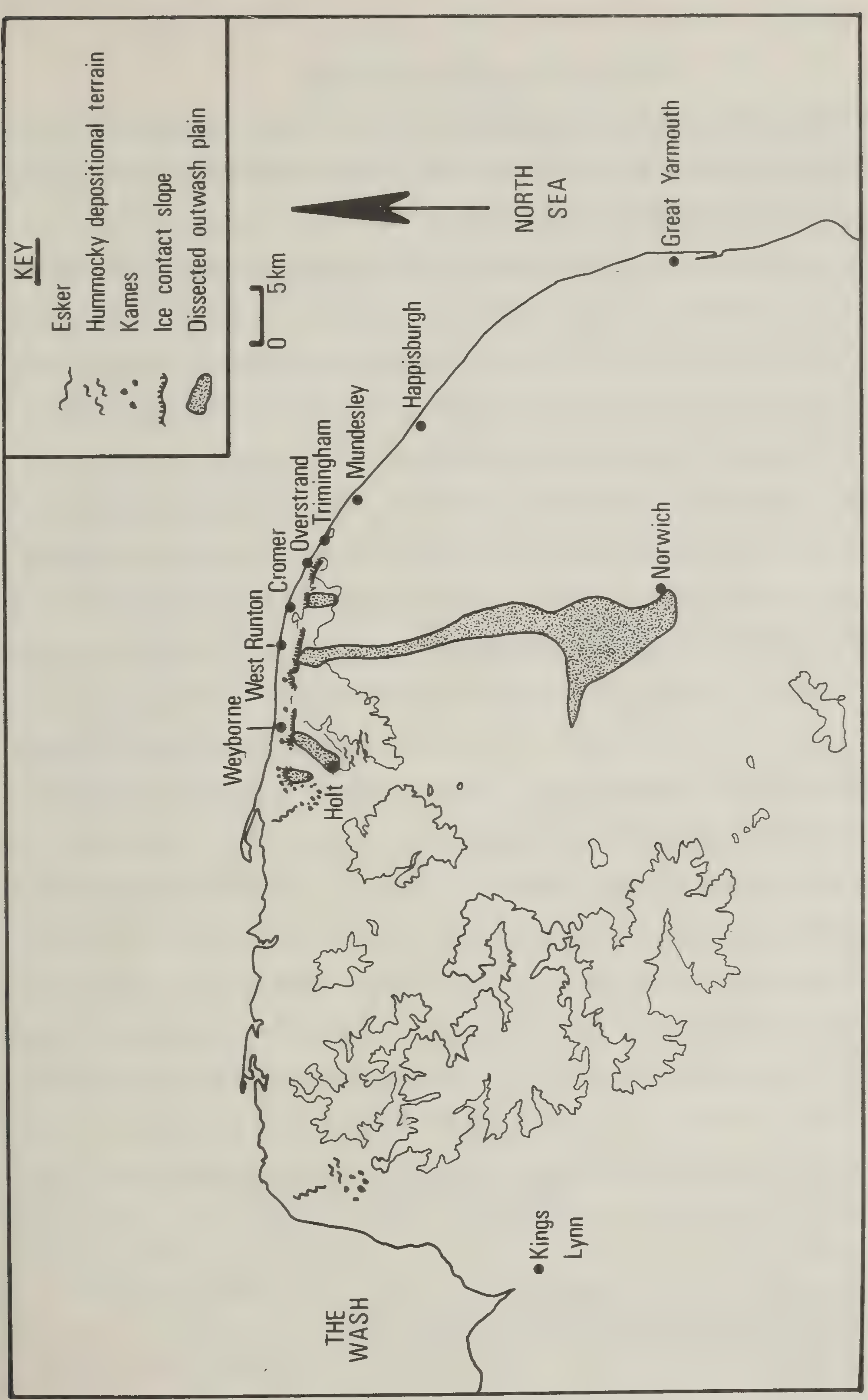
KEY
Esker
Hummocky depositional terrain
Kames
Ice contact slope
Dissected outwash plain
0 5km
NORTH SEA
Great Yarmouth
Happisburgh
Mundesley
Trimingham
Overstrand
Cromer
West Runton
Weyborne
Holt
Norwich
Kings Lynn
THE WASH

Figure 5. - The ice-contact features of north Norfolk and the 60m contour.

interpreted these as fluvioglacial outwash laid down in front of the advancing ice sheet. At Flordon, Dunston Common and Whitlingham these gravels are found beneath the Chalky Boulder Clay Facies.

In West Norfolk two extensive gravel sheets occur, the Lower Tottenhill Gravel; a poorly sorted flint gravel, and an overlying Upper Tottenhill Gravel. Only the lower gravel is considered to be glacially derived (Gallois, 1978) whereas the upper gravel is thought to represent a Pleistocene beach deposit. At Hunstanton there is an impressive series of ice contact deposits, similar to those of north-east Norfolk, but here associated with the Hunstanton Till. They comprise a large esker and series of kames (Boulton, in West, 1977).

5. MAJOR PROBLEMS OF THE GLACIAL GEOLOGY OF NORFOLK

A clear statement of what we know is the first step in identifying unsolved problems. We can conclude with confidence that:-

a) Glaciation of southern and central Norfolk occurred between the Hoxnian and Cromerian interglacials.

b) In east and south-east Norfolk at least, this was a multi-phase episode.

c) The Chalky Boulder Clay facies derived predominantly from the west and north-west and though possibly penecontemporaneous with the North Sea Drift Facies, in many places it was emplaced later.

d) A major ice front stationary line occurs in north Norfolk.

e) A major ice front stationary line occurs due north of Norwich.

There are a further set of problems which we are as yet unable to resolve:-

5a) The number of glacial events in East Anglia

Bristow and Cox (1973) suggested that the available lithostratigraphical evidence only demonstrates a single major glacial event in most of East Anglia. This view was supported by the studies of Perrin, Davies and Fysh (1973) who show that the Chalky Boulder Clay has had a uniform lithology; a view further endorsed by the Geological Society's Quaternary Era sub-committee (Mitchell *et al.* 1973) which discarded the "Gipping Till" glaciation of presumed Wolstonian age, previously identified in central East Anglia (West, 1963). Straw (1979) has however challenged these views and suggested that a Wolstonian glacial limit can be identified oriented south-west/north-east and passing just west of Norwich. However this view is incompatible with a number of pre- Wolstonian, Hoxnian interglacial sequences not covered by till in the area of Straw's Wolstonian glaciation. These occur in the Nar Valley (Stevens, 1960) in the Nene Valley (Horton, 1981) and at Barford and Dunston Common (Cox and Nickless, 1972; Phillips, 1976).

On the other hand Perrin, Rose and Davies (1979) have demonstrated that the Chalky Boulder Clay Facies of Eastern England shows smooth variation in lithological properties. From this they conclude that this facies was laid down during a single glacial event. However there is as yet no theoretical or empirical model which predicts the pattern of variation in tills of similar provenance laid down by successive glacial events. Without this, their data is difficult to interpret as a guide to a chronology.

5b) The relationship between the Anglian glacial stage and the European glacial sequence

The conventional correlation between glacial and interglacial events in East Anglia and on the European continent (Table 1) produces the surprising conclusion that whereas the Saalian glacial event in Europe was the most extensive Quaternary glaciation, far more extensive than that of the preceding Elsterian Stage, in eastern

England (and presumably in the rest of the country) it was during the Anglian (Elsterian) Stage that the ice sheets were most widespread. Bristow and Cox (1973) drew attention to this anomaly and in particular question the correlation between the Hoxnian interglacial and the Holsteinian interglacial of Europe (West, 1956) the basis for the Anglian/Elsterian and Wolstonian/Saalian correlation.

5c) The age of the drifts of North Norfolk

In north-west Norfolk in the Hunstanton area, and in north-east Norfolk from Blakeney to Trimingham (Fig.5) impressive accumulations of ice-contact fluvioglacial sediments occur. Such well-defined and diagnostic surface features are rare along the east coast of England, and absent south of the Waveney Valley. Unfortunately, the central zone of the north Norfolk coast, between the Hunstanton and Blakeney areas, is not well-known. If however we assume that there is a continuous belt of ice-contact sediments across the north Norfolk coast and, that they are of similar age, then a major problem arises. The Hunstanton deposits are commonly thought to be of Devensian age (Mitchell et al. 1973), implying that the Cromer Ridge must also be of Devensian age, as must the Contorted Drifts which lie at the surface to the north and east of the ridge. If however we project our correlations from the Mundesley area, where Phillips (1976) has identified Ipswichian deposits in a channel which may overlie the Contorted Drifts, one would conclude that the Cromer Ridge and the ice-contact phenomena of north Norfolk are of pre-Ipswichian age.

These conclusions are incompatible therefore some must be incorrect. The possible errors are:-

i) The premise that the similarity of lithology and soil development between the Hunstanton Till and the Devensian

Drab Till of Holderness (Mitchell et al. 1973; Madgett, 1975) is incorrect. The Hunstanton Till could be of similar age to the Contorted Drifts of north-east Norfolk belonging to the Anglian, or possibly Wolstonian stages.

ii) The Ipswichian beds of the Mundesley channel may not stratigraphically overlie the Contorted Drifts, or may themselves be affected by deformation (the field relationships are not clearly described).

iii) The ice-contact deposits of north-west Norfolk and north-east Norfolk are not of similar age, those to the west of Weybourne may be of Devensian age and those to the east pre-Ipswichian (Sparks and West, 1964; Straw, 1973).

One of us (GSB) is attracted to the hypothesis that the ice-contact landforms of north Norfolk are of the same age, and that this may be Wolstonian. It is possible that such a Wolstonian ice front, which also produced the Contorted Drifts, trended south-east through Trimingham and Mundesley and joined with the Saalian ice maximum in Holland. The Hunstanton deposits would thus also be of Wolstonian age and correlated with the Wolstonian of the Midlands. Thus the east Norfolk coast would be an important zone, intermediate between an area to the west where the Anglian/Elsterian glaciation was more extensive than the Wolstonian, and one in the east where the Saalian/Wolstonian) was most extensive. However another view is held by MHT and FCC, that the ice contact features and eskers relate to the last glacial period and much of the Contorted Drift was emplaced by an earlier glacial event and deformed during the Devensian.

Clearly the north Norfolk region is a key area for the Pleistocene chronology not only of East Anglia but of Britain.

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A GUIDE TO THE HOLOCENE GEOLOGY OF NORTH NORFOLK

B.M. Funnell* and I. Pearson+

ABSTRACT

Fourteen different sedimentary/faunal/floral environments have been recognised in the Holocene inter- and supra-tidal deposits of the North Norfolk coast, on the basis of aerial photographic survey and ground sampling.

Sedimentological and micropalaeontological characterisation of these surface sediments has allowed their recognition in borehole samples taken across the coastal zone in a series of N-S transects.

Sedimentation commenced around 8500 B.P. (= 6500 B.C.) with the accumulation of freshwater peats, which were progressively inundated from 6000 B.P. (= 5000 B.C.) onwards by marine waters that deposited extensive accumulations of inter-tidal silty sands and muds. In places there is clear evidence of marine regression/marsh emergence leading exceptionally to pine woodland growth at about 3000 B.P. (= 1000 B.C.), but generally the positions of major channels, tidal flats and marshes seem to have been stabilised in their present locations for at least 4000 years, either by the forming of barrier beaches, once they topped the high-tide mark, or by the influence of the underlying pre-Holocene topography.

1. INTRODUCTION

The North Norfolk coast, from Holme in the west to Weybourne in the east (a total distance of 40 km) is a zone of salt marshes and

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tidal flats, with associated barrier islands, gravel ridges, spits and dunes. This zone is up to 4 km wide in places. It is a classic area for the study of topography, physiography and the vegetational and historical development of such coastal areas (Cozens-Hardy 1924; Steers 1960, 1969; Chapman 1960). It has also been the target of special studies of modern sedimentation processes (Allen and Friend 1976; Battacharyya 1967; Cambers 1975; Clayton 1977; Hardy 1964; McCave 1978; Pethick 1981; Roy 1967; Vincent 1980), but until 1978 little attention had been given to the development of this coastline and its deposits over the longer timescale of post-glacial (= Holocene) history. In fact the only preliminary attempts to assess the pre-historical development of the area on the basis of sedimentary evidence are those of Murphy and Funnell (1980) and Pethick (1980). In 1980 one of us (I.P.) started research on an NERC-studentship to study the contemporary environments of sedimentation and their Holocene development. This paper is a preliminary sketch of the primary results written for the British Association meetings in Norwich in 1984.

2. PRESENT-DAY ENVIRONMENTS

Most of the area under consideration is inter-tidal. The tidal range varies from 5 to 6 metres at Springs to 2 to 3 at Neaps, and peak spring tidal currents just offshore range from about 0.75 metres per second in the west to just over 1.00 metres per second in the east. Some of the area is naturally supra-tidal, consisting both of gravel ridges thrown up by storms and of dunes constructed from wind-blown sand, itself derived from the extensive sand flats and beaches. There are also substantial supra-tidal (or extra-tidal) areas that have been created through artificial embankment and drainage. All of these environments have been subjected to careful aerial photographic, sedimentological and microfaunal analysis to (a) determine their present distribution, and (b) characterise them sedimentologically and palaeontologically (Pearson, Funnell and McCave, in prep.), so that they can be recognised in Holocene borehole materials.

The environments recognised in this way are shown in Table 1 and Fig. 1. Their salient sedimentary characteristics are described below.

Table 1 Sedimentary Environments of the North Norfolk Coast

(a) Outcrops of earlier Holocene sediment
(b) Inter-tidal Gravels
(c) Channel Sands
(d) Inter-tidal Sands
(e) Inter-tidal Silty Sands
(f) Inter-tidal and Creek Muds
(g) Lower Salt-Marsh
(h) Upper Salt-Marsh
(i) *Phragmites* Marsh
(j) *Suaeda fruticosa* Scrub
(k) Dunes
(l) Scrub
(m) Conifer Plantations
(n) Reclaimed Land

(a) Outcrops of earlier Holocene sediment

Whereas most of the sedimentary environments on the North Norfolk coast are depositional, i.e. zones of net accumulation of sediment, in some places erosion is occurring and older Holocene sediments are exposed. This is particularly so where onshore migration (roll-over) of beaches or barrier beaches is occurring, or where sediment starvation occurs in areas west of accumulating spits, and earlier deposits become exposed on the lower part of the beach face at low tide. Perhaps the most spectacular example is the forest of fallen pine trunks, sometimes still attached to their roots, which can usually be seen on the foreshore in front of Titchwell RSPB Nautre Reserve. The peat in which these pines were rooted, and the underlying salt-marsh clay, can be seen extending both westward, and eastward to the Brancaster Golf Clubhouse. Peat from this peat-soil level, obtained from boreholes across the marshes at Brancaster indicate a radiocarbon age of 2790 ± 40 years B.P. (= 840 years B.C.; SRR 2386).

Salt-marsh clays with Scrobicularia plana also outcrop in front of Scolt Head Island. Shells and wood from these have been dated to 927 ± 90 and 423 ± years B.P. (= 1023 and 1527 years A.D.).

These outcrops indicate that supra-tidal forest and high inter-tidal mud/low salt-marsh environments stretched further seaward (northward) around 850 B.C. and 1400 A.D. at Titchwell - Brancaster and Scolt Head Island than they do at the present-day.

(b) Inter-tidal Gravels occur in large patches, forming the present-day beaches of Blakeney Spit and Scolt Head Island barrier beach, with their characteristic recurved lateral beaches extending landward marking the present and former westward terminations of these structures. They define the high energy zone of breaking waves and storm beaches are raised well above normal high-tide levels by the exceptional conditions associated with winter tempests. In addition

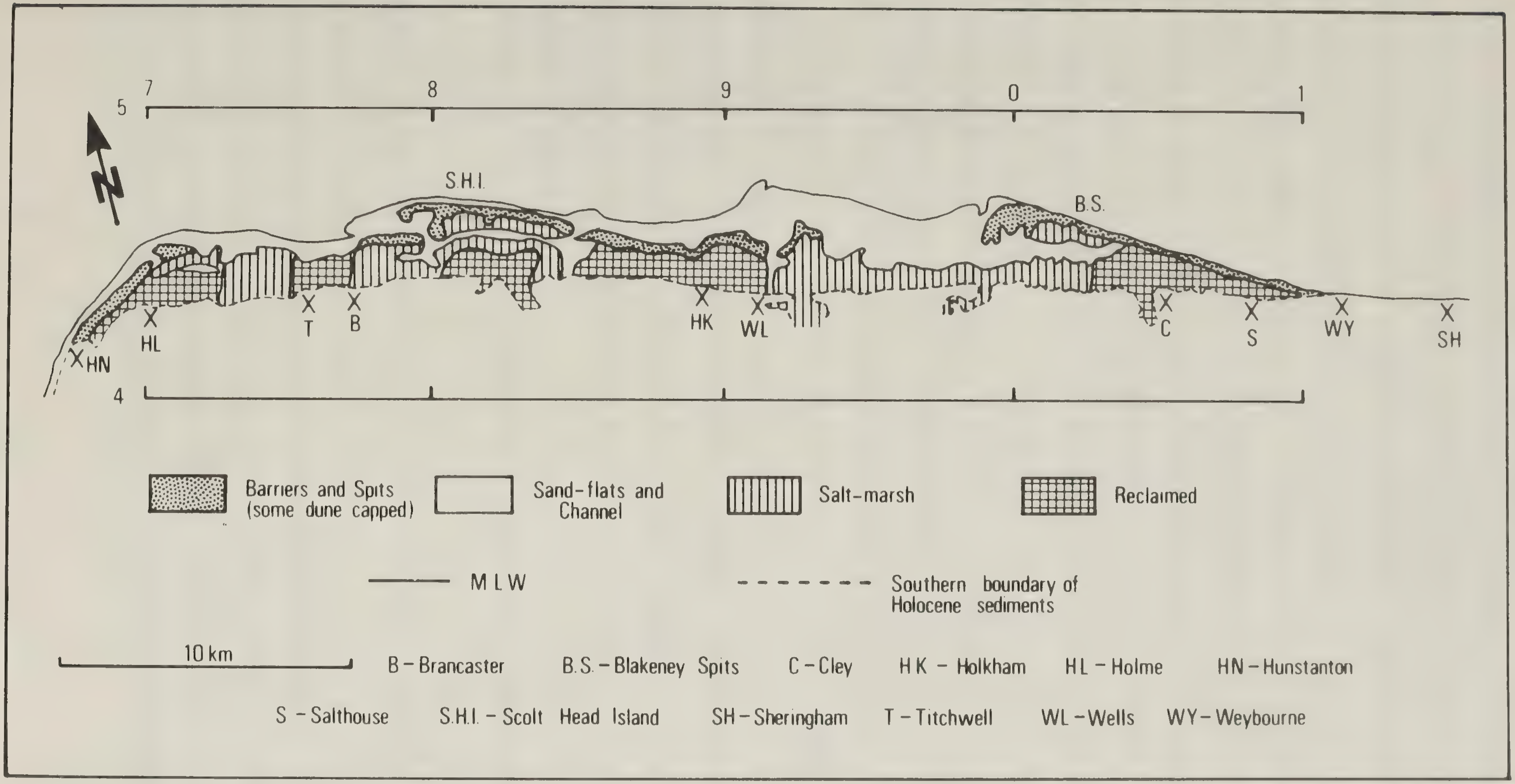

5
4
7
8
9
0
1
N
S.H.I.
B.S.
HN
HL
T
B
HK
WL
C
S
WY
SH
Barriers and Spits (some dune capped)
Sand-flats and Channel
Salt-marsh
Reclaimed
M L W
Southern boundary of Holocene sediments
10 km
B - Brancaster
B.S. - Blakeney Spits
C - Cley
H K - Holkham
H L - Holme
H N - Hunstanton
S - Salthouse
S.H.I. - Scolt Head Island
SH - Sheringham
T - Titchwell
WL - Wells
WY - Weybourne

Figure 1. Sedimentary Environments of the North Norfolk Coast

to the lateral beach ridges, partially buried by later inter-tidal flat and salt-marsh sedimentation, which indicate the former position of the western extremities of Blakeney Spit and Scolt Head Island, there are a considerable number of partially buried arcuate beach ridges in the salt-marshes further to the south, indicating an earlier generation of smaller, more numerous, miniature "Scolt Head Islands".

The source of the gravels forming these beaches is not altogether clear. In the case of Blakeney Spit a source in the glacial cliffs of north-east Norfolk by westward beach drift is altogether apparent, but for Scolt Head Island several kilometres of sandy beach intervene to the east and in the absence of any cliff erosion or significant inflow of rivers to provide such gravel along this stretch of coast an offshore supply of glacial gravel can only be surmised.

(c) Channel Sands

In the main 'flood' and 'ebb' channels by which tidal flow reaches and leaves the creeks of the salt-marshes, the sands are subject to stronger currents and often include a significant gravel fraction. They also develop sub-aqueous sand wave structures. The main grain size of the sand ranges from 2.2 to 1.3Ø and therefore tends to be the coarsest sand along the coast.

(d) Inter-tidal Sands

Copious supplies sand of are available along the North Norfolk coast, from onshore movement of sea-bed sands left behind by the last glaciation and from westward movement of the products of erosion of the cliffs of glacial deposits of north-east Norfolk. These sands occur mainly in the lower part of the inter-tidal zone but in places may merge landwards into beach-face sand deposits and aeolian dunes.

The range of mean grain sizes is slightly finer at the fine end and markedly finer at the coarse end than channel sands, but still overlaps them overall. The larger grains appear to be preferentially removed to beach bar crests.

(e) Inter-tidal Silty Sands

Where areas of inter-tidal sand deposition are incompletely drained at low tide (because of low gradients), or where deposition occurs landward of beach bar development, then thin drapes or flasers of mud occur on the surface of the sand giving a silty sand environment.

(f) Inter-tidal and Creek Muds

Where deposition occurs in sheltered conditions, in salt-marsh creeks, or landward of spits and barrier islands, or even seaward of spits and barriers - if high beach bars are developed seaward of them, then muds accumulate.

These muds contain much material with a mean grain size of between 4.5 and 5.5∅, but also some with a mode of 1.5 to 2.5∅, derived from the inter-tidal sand areas.

(g) Lower Salt-Marsh

These are muddy areas colonised by algae and Zostera (eel grass) occurring just above the inter-tidal muds. Their mechanical composition is almost identical to the inter-tidal and creek muds.

(h) Upper Salt-Marsh

The transition between lower and upper salt-marsh is marked by the first appearance of Halimione portulacoides (sea purslane) in the flora. Usually on this coast this first occurs at +2.05 m O.D. but in some of the more open areas of marsh its first appearance may be as high as +2.45m O.D. The upper salt-marsh is the most extensive type of salt-marsh on this coast.

The mechanical composition of upper salt-marsh muds is distinguishable from the lower salt-marsh on mean grain size, which is finer.

(i) **Phragmites** Marsh

At the landward edge of the upper salt-marsh and adjacent to incoming river water, where the imput of freshwater drainage makes the water brackish, stands of Phragmites communis (common reed) develop, leading to peat accumulation.

(j) **Suaeda fruticosa** Scrub

On drier ground at the edge of the upper salt-marsh, at the transition from marsh to dune environments, and along the courses of partially buried, but gravelly or sandy and therefore better drained relict barriers, ridges and laterals, occurs the characteristic Suaeda fruticosa (shrubby seablite). It also occurs along the levees of the larger creeks.

(k) Dunes

Dunes are a conspicuous feature topping the main beach ridges and the major laterals. They obtain their sand from the wind-swept areas of inter-tidal sand which are exposed and dry out between successive tidal cycles. The biogenic (skeletal) carbonate they initially contain is progressively leached out as the dune ages and its soil profile develops. Colonisation by Ammophilia arenaria (marram grass) and Agropyron junceiforme (sand twitch) is typical, but with time, especially in the swales between individual dunes, a much more diverse vegetation or grass sward may develop.

The range of mean grain size for dune sands is less than for inter-tidal sands, and values usually fall within the lower part of the inter-tidal sand range, reflecting their derivation from the finer grain-size population of the intertidal sands.

(l) Scrub

With increasing maturity of soil profiles on the better drained deposits, particularly in the shelter of high dunes, natural scrubland develops.

(m) Conifer Plantations

Typically, well-drained soils, mainly old dunes, when subject to human intervention, have been given over to conifer plantations.

(n) Reclaimed land

Finally, substantial areas of high salt-marsh have in the past been embanked and drained to form pasture and occasionally arable land. Most of these areas are still secure, but some between Brancaster and Titchwell, are at present being reclaimed again - not by man, but by the sea.

3. HOLOCENE ENVIRONMENTS

The development of the North Norfolk coast during the Holocene or Post-Glacial epoch, approximately the last 10,000 years, has been investigated by a systematic sequence of boreholes. These were carried out as a series of north-south transects across the coastal marshland from Holme in the west to Cley in the east. Samples were obtained using a "Minuteman" powered auger to depths of up to 8 metres. Four of the profiles obtained; those at Brancaster, Scolt Head Island, Holkham, and Cley are illustrated in Figs. 2 to 5.

During the Devensian stage of the Pleistocene, immediately prior to the Holocene, continental glaciers occupied northern N.W. Europe, including Scotland and Northern England, extending almost or just to the present-day position of the north coast of Norfolk. At that time, however, sea-level was very much lower than at the present-time, (because of the massive and general withdrawal of water from the oceans to form the greatly enlarged and mainly land-based polar and continental glaciers of that time). Estimates of the amount of lowering vary, and indeed the local effects vary because of factors such as the isostatic loading and depression of land areas by the weight of glacier ice. Neverthless a global lowering of sea-level of between 100 and 150 metres is highly probable and certainly the whole of the southern North Sea including the North Norfolk coast would have been subaerial (i.e. terrestrial) at that time.

Evidence of rising sea-levels in the southern North Sea after the glacial stage, as water was returned to the oceans by the wholescale melting of glacier ice, is found in the widespread distribution on the floor of the southern North Sea of fossil cockle (Cerastoderma edule) shells which are radiocarbon-dated to around 8,500 B.P. (= 6,500 B.C.).

It is at about this time that our record of Holocene sedimentation on the North Norfolk coast begins. Rising sea-levels clearly impeded freshwater drainage from the present coastal area and groundwater levels rose in concert leading to freshwater peat accumulation all along the present coast, everywhere resting on the pre-existing surface which we have found to be variously composed of Chalk (at Holkham), glacial till (at Holme) and presumed fluvio-glacial sands (at Brancaster). Significantly the apparent cliff-line at the southern limit of the Holocene deposits (e.g. at Stiffkey and Salthouse) is not approached by high-energy (i.e. beach type) marine

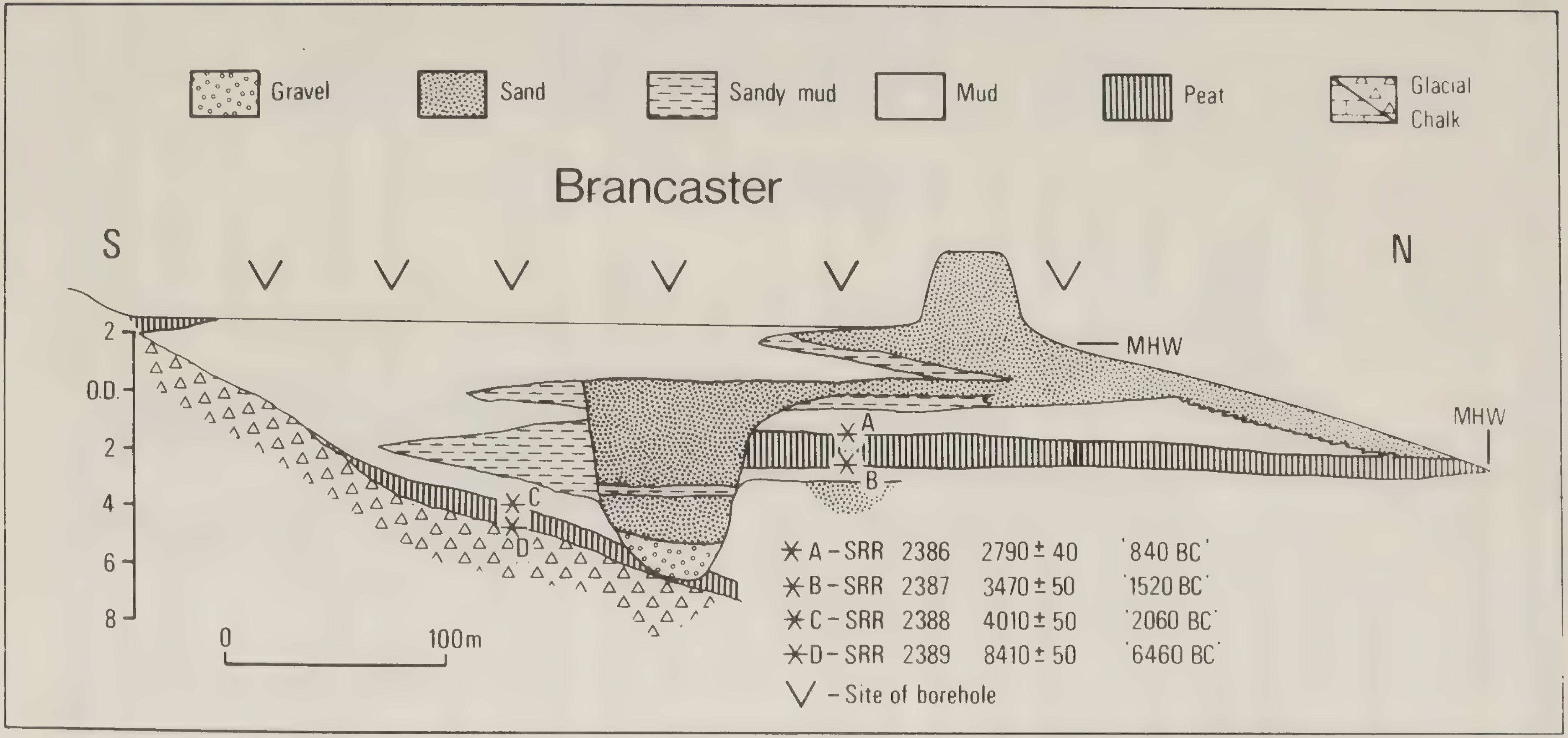

Gravel
Sand
Sandy mud
Mud
Peat
Glacial Chalk
Brancaster
S
N
MHW
MHW
2
0.D.
2
4
6
8
0
100m
A
B
C
D
A - SRR 2386 2790 ± 40 '840 BC'
B - SRR 2387 3470 ± 50 '1520 BC'
C - SRR 2388 4010 ± 50 '2060 BC'
D - SRR 2389 8410 ± 50 '6460 BC'
V - Site of borehole

Figure 2. Cross-section of the marshes at Brancaster

deposits at any time during the Holocene. If it is a marine feature therefore it must have been cut in an earlier (perhaps the Ipswichian = Eemian) interglacial, although we have encountered no actual deposits from that period.

Following the accumulation of the freshwater peats the rising sea-level progressively inundated them leading to inter-tidal deposition. In several places a succession from inter-tidal muds upwards into higher salt-marsh sedimentation can be followed. At one period (around 3500 B.P. = 1500 B.C.) freshwater peat began to accumulate again on these higher salt-marsh deposits and opposite Titchwell a pine wood was even established. This pine wood may have been relatively short-lived. Superficial examination of the fallen trunks in the deposit on the beach at Titchwell suggests that only one generation of trees may have been produced before the sea again gained access. Radiocarbon dates suggest that the period of peat accumulation may have lasted only 700 years. A similar, but less spectacular transition to higher inter-tidal or supra-tidal deposition seems to occur throughout our coastal sections at this time. The depth of this horizon relative to present salt-marsh levels is -3 metres, suggesting subsidence of 3m in the last 2750 years, or about 1m per 1,000 years.

Whereas the evidence of lower sea-levels relative to the contemporary sedimentation surface at about 2750 years B.P. is fairly general in the coastal sequences we have examined, it is also equally clear over large areas that some environments have been very persistent in time in the same places. Thus some boreholes have proved considerable thicknesses (e.g. 4 metres) of inter-tidal muds alongside equal thicknesses of channel sands, implying the continuing

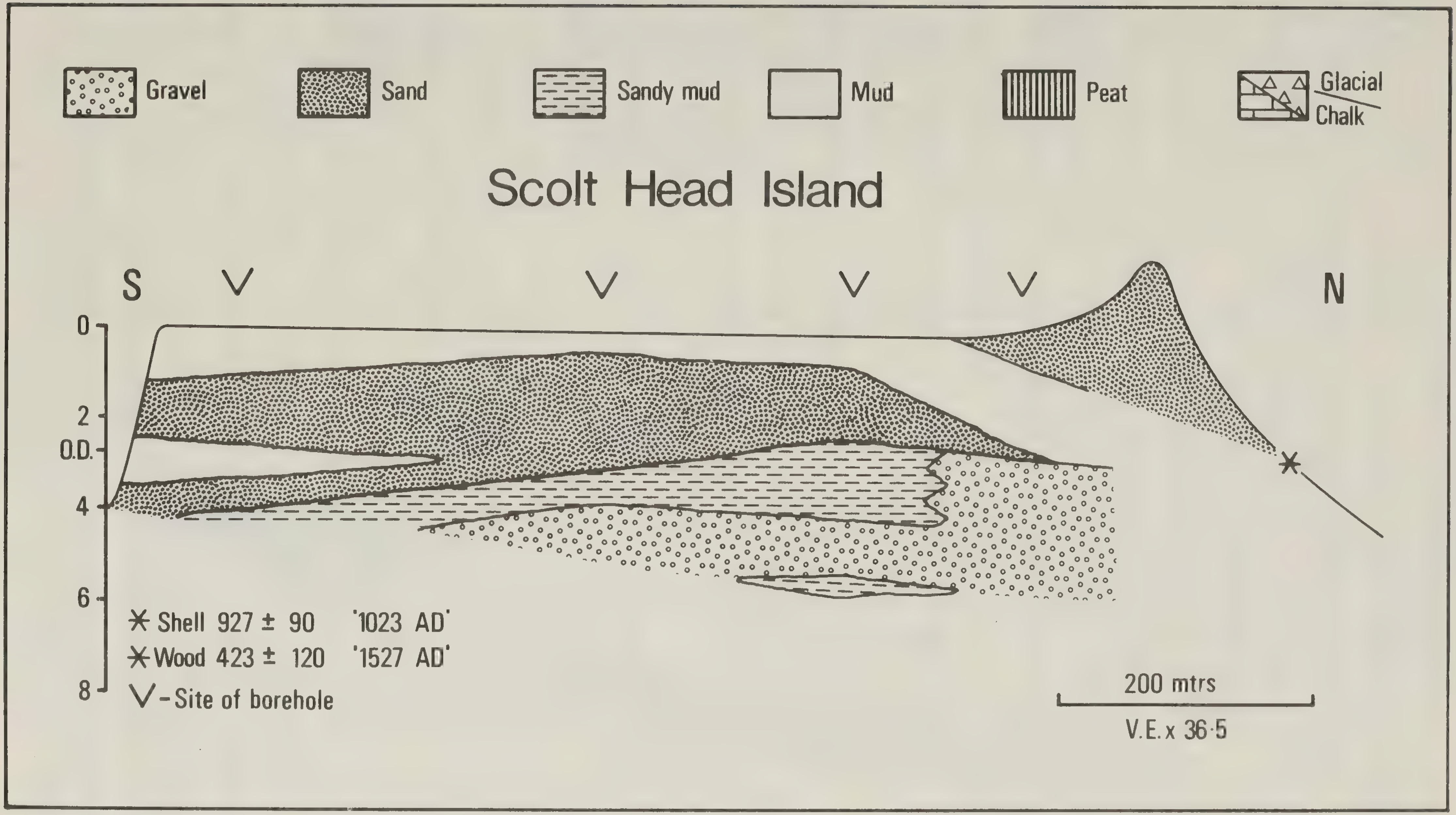
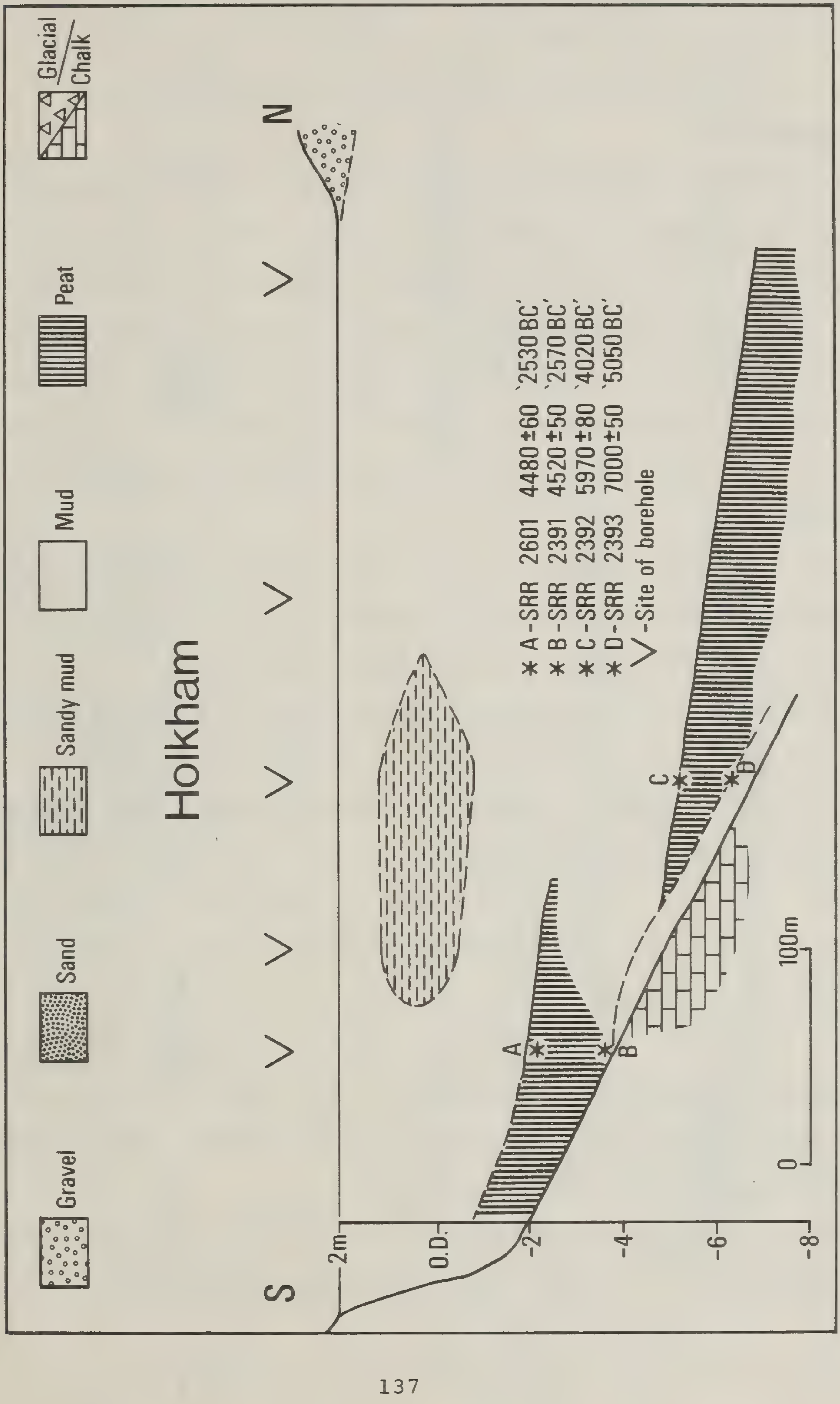

Gravel
Sand
Sandy mud
Mud
Peat
Glacial
Chalk
Scolt Head Island
S
N
0
2
O.D.
4
6
8
✳ Shell 927 ± 90 '1023 AD'
✳ Wood 423 ± 120 '1527 AD'
V - Site of borehole
200 mtrs
V.E. x 36·5

Figure 3. Cross-section of Scolt Head Island

presence of channels and inter-tidal muds or lower salt-marsh alongside one another for substantial periods of time (say 4000 years). Indeed one of the important outcomes of these investigations has been the evidence that the present-day distribution of environments is largely determined by structures that were established relatively early in the Holocene or even in the preceding glacial stage. By comparison the observed and historical evolution of such structures as Scolt Head Island and Blakeney Spit (Steers 1960, 1968) are only relatively minor modifications of a pattern that was established at least 4000 years ago. The depression between Blakeney Spit and the southern margin of Holocene deposition, which is infilled by several metres of inter-tidal deposits seems to be a persistent and origial feature that dates back to the initiation of Holocene sedimentation in the vicinity. This calls into question the concept of the position of Blakeney Spit being wholly determined by an equilibrium between progradation and westward longshore drift. It may in fact be partially determined by the position of a ridge of underlying glacial material. A similar view may be taken of the major channels which run parallel to the coast, in places inside barrier beaches such as Scolt Head Island. Their position seems to have been determined mainly by the original location of barrier beaches when they first became fixed above sea-level. Subsequent deposition in the channels has gone on in step with accumulation rates on the surrounding flats and marshes, raising the whole system vertically in time without lateral displacement. Whether this continues into the future, and whether therefore this coastline retains its present attractive distribution of different environments, will no doubt depend not only on movements of sea-level (positive or negative), but also in the former case on


Gravel
Sand
Sandy mud
Mud
Peat
Glacial
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S
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* A-SRR 2601 4480±60 '2530 BC'
* B-SRR 2391 4520±50 '2570 BC'
* C-SRR 2392 5970±80 '4020 BC'
* D-SRR 2393 7000±50 '5050 BC'
V-Site of borehole

Figure 4. Cross-section of the marshes at Holkham

whether sediments such as mud or sand continue to be supplied in sufficient quantities (from offshore or from erosion of cliffs in Norfolk and Lincolnshire) to allow equilibrium to be maintained.

Acknowledgements

I.Pearson acknowledges the award of an N.E.R.C. Research Studentship during the period that these investigations were undertaken. Radiocarbon dates were supplied by the N.E.R.C. Radiocarbon Dating Unit at East Kilbride. We also acknowledge the numerous permissions to work on privately and publicly owned land (including the National and the Norfolk and Norwich Naturalists' Trust), without which these results would not have been possible.

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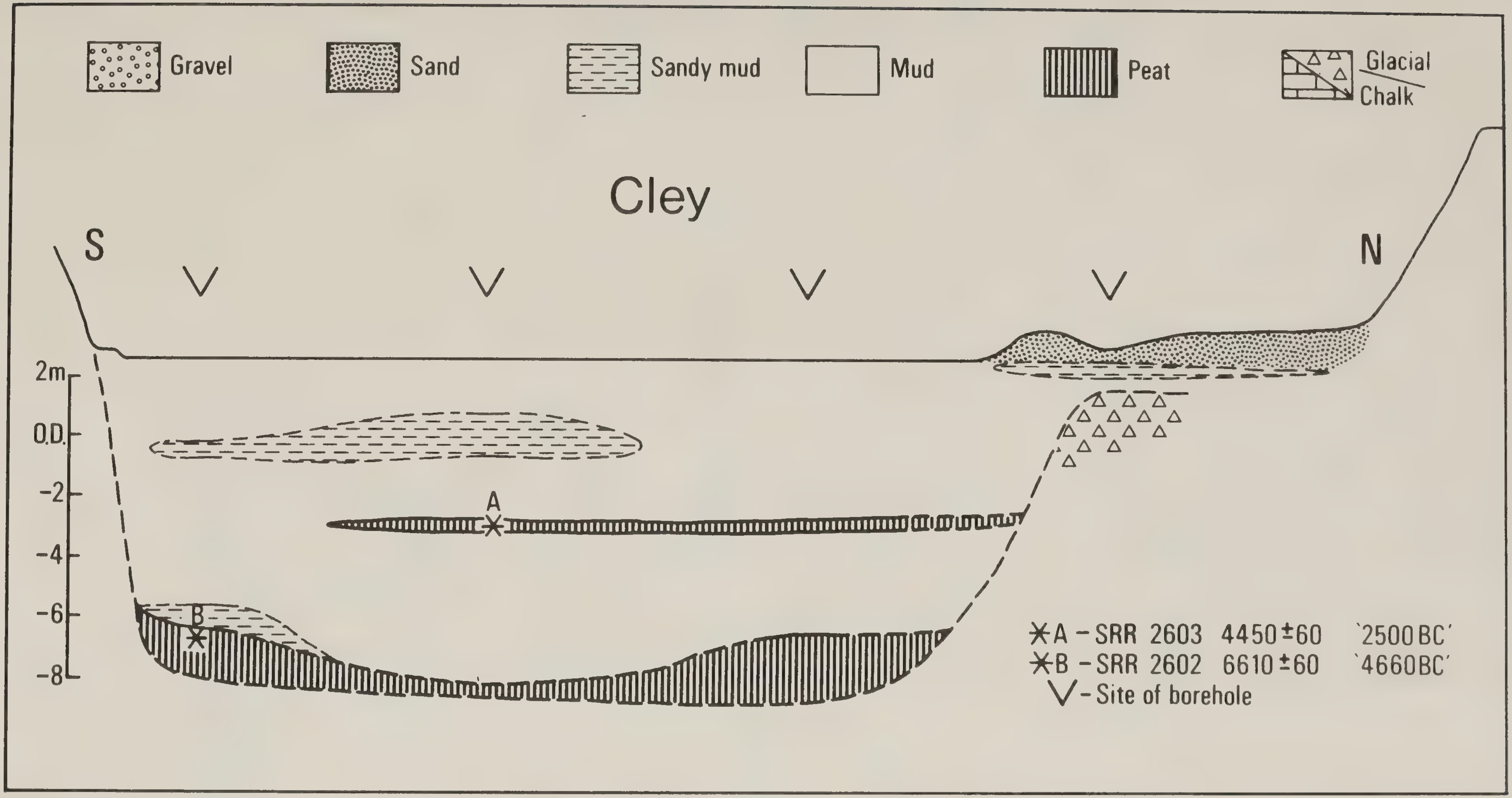
Gravel
Sand
Sandy mud
Mud
Peat
Glacial
Chalk
Cley
S
N
2m
O.D.
-2
-4
-6
-8
A
B
✱A – SRR 2603 4450±60 `2500BC'
✱B – SRR 2602 6610±60 `4660BC'
V – Site of borehole

Figure 5. Cross-section of the marshes at Cley

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CONTENTS	"EAST ANGLIAN GEOLOGY"	Page
Editorial		1
Gallois, R.W.	The Late Jurassic to Mid Cretaceous rocks of Norfolk	3
Mathers, S.J., Zalasiewicz, J.A. and Balson, P.S.	A guide to the geology of South-East Suffolk	65
Boulton, G.S., Cox, F., Hart, J. and Thornton, M.	The glacial geology of Norfolk	103
Funnell, B.M. and Pearson, I.	A guide to the Holocene geology of North Norfolk	123

The Geological Society of Norfolk exists to promote the study and knowledge of geology, particularly in East Anglia, and holds monthly meetings throughout the year.

Visitors are welcome to attend the meetings and may apply for membership of the Society. For further details write to the Secretary: Miss Diana Smith, Castle Museum, Norwich NR1 3JU.

Copies of the Bulletin may be obtained from the Secretary at the address given above; it is issued free to members.

The illustration on the front cover comprises on the left the logo of the British Association meeting at the University of East Anglia, Norwich, held in 1984, and on the right the logo of the Geological Society of Norfolk.

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P.S. 146

BULLETIN OF THE GEOLOGICAL SOCIETY OF NORFOLK

(FOR ARTICLES ON THE GEOLOGY OF EAST ANGLIA)

No.35 1985

CONTENTS INCLUDE:

Jurassic & Cretaceous of Upware
Chalk Fossils
Coralline Crag Foraminifers
Pleistocene Birds
Catton Pit S.S.S.I.

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BULLETIN of the GEOLOGICAL SOCIETY OF NORFOLK

No. 35 June 1985

Editor: B.M. Funnell, School of Environmental Sciences,
University of East Anglia, Norwich NR4 7TJ

Assistant Editor: P.G. Cambridge, 258 Bluebell Road, Norwich NR4 7LW

EDITORIAL

Following the successful publication of Bulletin No. 34 'East Anglian Geology', we now return to the customary size and format for Bulletin No. 35. It contains a useful variety of articles, ranging from the late Jurassic to early Cretaceous deposits of Upware in the west of the region, via some notes on Chalk fossils (and the Catton Sponge Bed S.S.S.I.) from around Norwich, on to Coralline Crag foraminifers from Suffolk, and general review of Pleistocene bird remains in S.E. England. As always we are very grateful to our contributors who have taken the time and trouble to compile these papers. Without their efforts there would be no Bulletin. At present we have no back-log of original papers and look forward to receiving some new contributions for Bulletin No. 36 (currently scheduled for April 1986).

Potential contributors should note that although we prefer manuscripts to be submitted in typewritten copy we will accept neatly handwritten material. It is most helpful if the style of the paper, in terms of capitalization, underlining, punctuation, etc., is made to conform strictly to those normally used in the Bulletin. All measurements should be given in metric units. The reference list is the author's responsibility and should always be carefully checked.

Illustrations are important. They should be drawn with thin dense black ink lines. Thick lines, close stipple or patches of solid black should be avoided as these tend to spread in the printing process usually employed. Original illustrations should, before reproduction, be not more than 175 mm by 225 mm. Full use should be made of the first (horizontal) dimension, which corresponds to the width of print on the page, but the second (vertical) dimension is an upper limit only. Half-tone (photographic) plates can also be accepted, providing the originals exhibit adequate contrast, and when their use is warranted by the subject matter.

Authors are reminded that the Bulletin of the Geological Society of Norfolk exists to publish research papers, notes or general articles relevant to the geology of East Anglia as a whole, and does not restrict consideration to articles covering the geology of Norfolk alone.

Corrigenda

The following corrigenda to articles in Bulletin No. 35 should be noted:

Mathers, Zalasiewicz and Balson

p.66, lines 3, 8, 10 and 13; for 'Eocene' read 'Palaeogene'
p.67, Table 1; " " " "
p.81, Fig. 5, East Anglian column' 'THURIAN' should read 'THURNIAN'
p.86, line 4 from bottom; for 'during the' read 'by The'
p.95, line 7 from bottom; 'remaions' should read 'remains'
p.98, line 1; 'Foraminfera' should read 'Foraminifera'

Boulton, Cox, Hart and Thornton

p.111, line 5; 'falls' should read 'fall'
line 9; insert after 'Trimingham', but further north we feel ...'
line 12; delete comma
p.118, line 4 from bottom;insert after 'some','of the premises on which they are based'

Funnell and Pearson

p.128, line 6 from bottom; 'sand of' should read 'of sand'
p.136, line 13; 'origial' should read 'original'

B.M. Funnell
P.G. Cambridge

Bull. geol. Soc. Norfolk, 35, 3-38 June 1985

JURASSIC AND CRETACEOUS DEPOSITS OF UPWARE, CAMBRIDGESHIRE
(a review and excursion report)

S.R.A. Kelly*

Abstract

The geology of the Upware region is reviewed, concentrating on the Upper Jurassic and Lower Cretaceous deposits. A detailed survey of the literature is given. An itinerary covers the Upware Limestone and Lower Greensand which are the only units outcropping today. A full faunal and floral list is given for the particularly well exposed Upware Limestone, and a facies interpretation of the fossil reef that makes up this stratigraphic unit is made.

Introduction

Upware has always been a popular site for geologists to visit. The earliest reference to field work there is an account in the Cambridge Chronicle for 10 April 1835 which was republished in full by Clark and Hughes (1890, pp.491-494). The advertisement for the meeting is reproduced in Figure 1. Apparently a class of some 60 or 70 academic horsemen attended the energetic Professor Adam Sedgwick's novel expedition. After some difficulties in the 'galt' near Reach where two horses had to be dragged out of the mire with ropes, they reached the stone pits at Upware. Here the 'party halted for some time; and the geological relations of the stone bands were explained by hypothetical section'. After Upware nearly half the company deserted and returned to Cambridge, but the stalwarts carried on to Ely and were back in Cambridge by 8.30 pm, after some 40 miles in the saddle!

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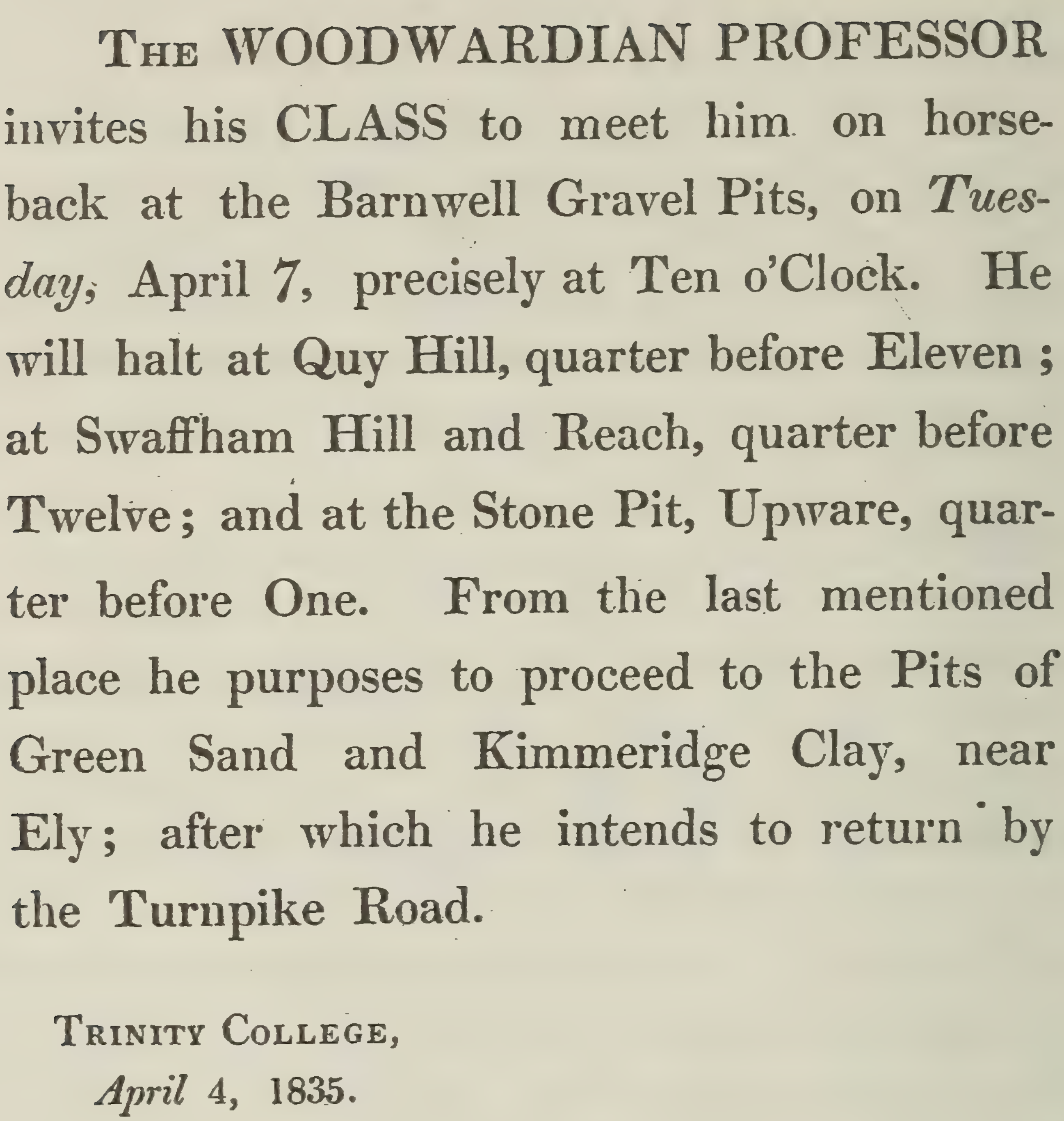

THE WOODWARDIAN PROFESSOR invites his CLASS to meet him on horseback at the Barnwell Gravel Pits, on *Tuesday*, April 7, precisely at Ten o'Clock. He will halt at Quy Hill, quarter before Eleven; at Swaffham Hill and Reach, quarter before Twelve; and at the Stone Pit, Upware, quarter before One. From the last mentioned place he purposes to proceed to the Pits of Green Sand and Kimmeridge Clay, near Ely; after which he intends to return by the Turnpike Road.

TRINITY COLLEGE,
April 4, 1835.

Fig. 1 Copy of an original advertisement for a field excursion to Upware led by Professor Adam Sedgwick in 1835 (Reduced: Sedgwick Museum)

Jurassic & Cretaceous of Upware

The aim of the Geological Society of Norfolk's (30 April 1983) visit was to examine the inlier of late Jurassic rocks surrounded by early Cretaceous strata near Upware in Cambridgeshire. The general stratigraphy was demonstrated as far as the outcrop allowed, and the full stratigraphy is summarised in Figure 2. At present, good outcrops of the Corallian occur, the Lower Greensand is poorly exposed, and other units not exposed at all. A summary of the history of events relating to Upware in the late Jurassic and early Cretaceous is given, together with reference to most of the geological works relevant to this period and place. In Appendix 1, important exposures made during excavations for pylons across the Isle of Upware and recorded by Dr. C.L. Forbes are shown on a map. Appendix 2 is a revised list of the Corallian Upware Limestone fauna and flora.

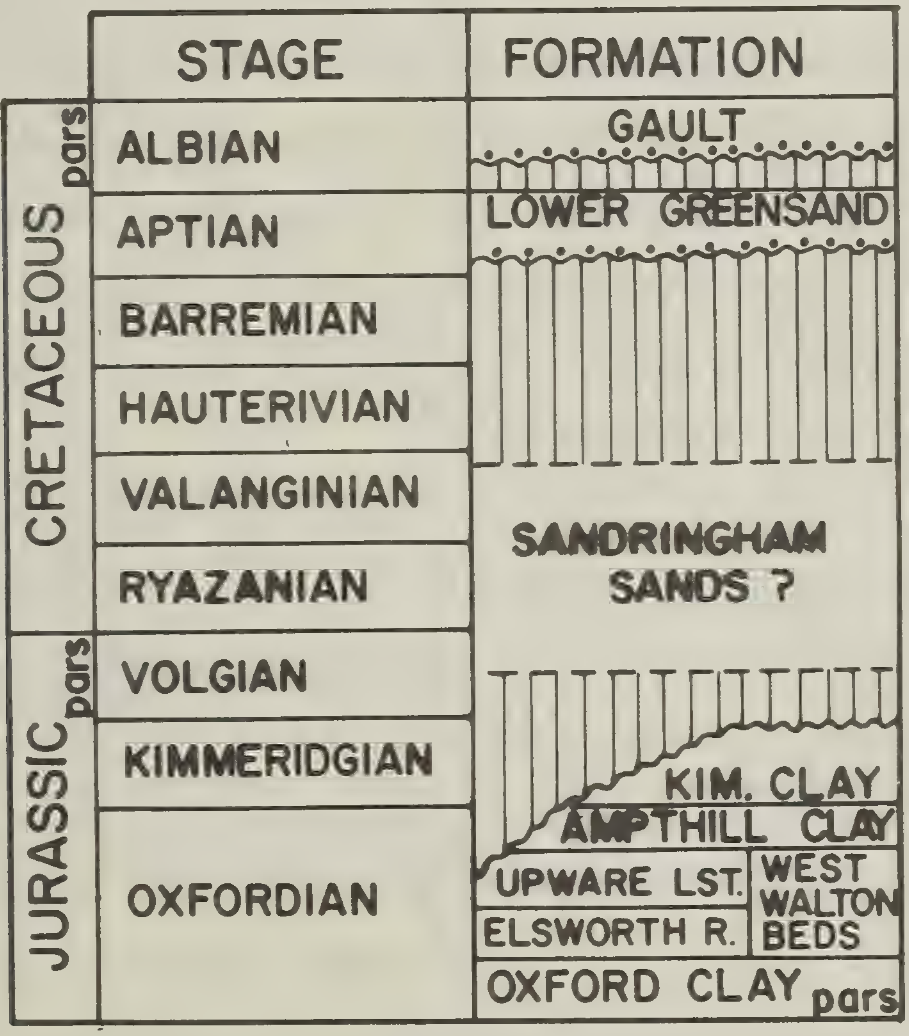
STAGE
FORMATION
CRETACEOUS pars
JURASSIC pars
ALBIAN
APTIAN
BARREMIAN
HAUTERIVIAN
VALANGINIAN
RYAZANIAN
VOLGIAN
KIMMERIDGIAN
OXFORDIAN
GAULT
LOWER GREENSAND
SANDRINGHAM SANDS ?
KIM. CLAY
AMPTHILL CLAY
UPWARE LST.
ELSWORTH R.
WEST WALTON BEDS
OXFORD CLAY pars

Fig. 2 The ages of the strata represented at Upware

The geology of the Upware region has been summarised or incorporated in a number of regional studies: Bonney (1875, Appendix 1); Penning and Jukes-Browne (1881); Reed (1897); Fearnsides (1904); Brighton (1938); Hey and Perrin (1960); Chatwin (1961); Forbes (1965); Torrens and Callomon (1968); Worssam and Taylor (1969). The 'Isle of Upware' is really a peninsular, elongated in a north-south ridge but connected to the east by further elevated land. Prior to drainage of the Fens it was surrounded by peat marsh. Evidence below suggests that this area formed an island or topographic high at several times during the Mesozoic. The outcrop of Jurassic strata stretches about 5 km northwards from Upware and is up to 1.5 km wide. At its greatest elevation it is only about 7m above Ordnance Datum, with the surrounding Fenland at only about 3m. To the east lies Wicken Sedge Fen and to the west the River Cam (Fig. 3). The core of the 'Isle' is composed of Oxfordian limestsones of the West Walton Beds, mainly the Upware Limestone (Gallois and Cox, 1977), with some peripheral outcrops of overlying Ampthill Clay. Overlying these with marked unconformity lies the Cretaceous Lower Greensand, and upon this with further unconformity the Gault. A generalised cross section of these relationships is shown in Figure 4.

It is interesting to note that the Palaeozoic basement was estimated by Bullard et al. (1940, Fig. 14) as being about 200m below the surface at Upware. Subsequent borings nearby show actual depths of -107m OD at Cambridge and -127m OD at Soham (Worssam and Taylor, 1969). The proximity of the London Platform has important consequences for the history of the region (see below). Chroston and Sola (1982) gave a review of other deep boreholes and seismic refraction data mainly from Norfolk, but their study overlaps with the

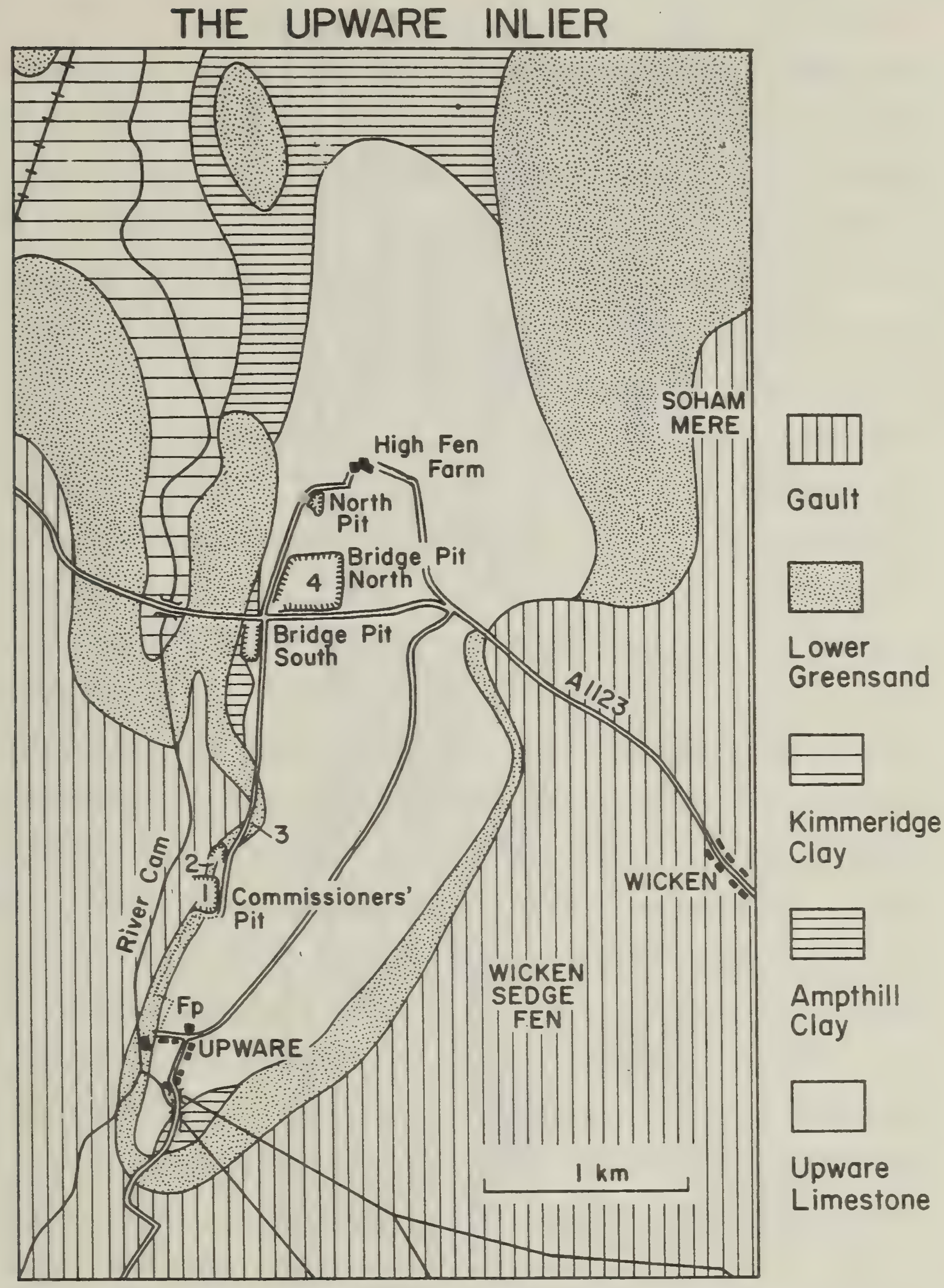
THE UPWARE INLIER
SOHAM MERE
High Fen Farm
North Pit
4
Bridge Pit North
Bridge Pit South
A1123
3
2
1
Commissioners' Pit
River Cam
WICKEN
WICKEN SEDGE FEN
Fp
UPWARE
1 km
Gault
Lower Greensand
Kimmeridge Clay
Ampthill Clay
Upware Limestone

Fig. 3 Map of the geology (solid) of the Isle of Upware, based on IGS Sheet 188

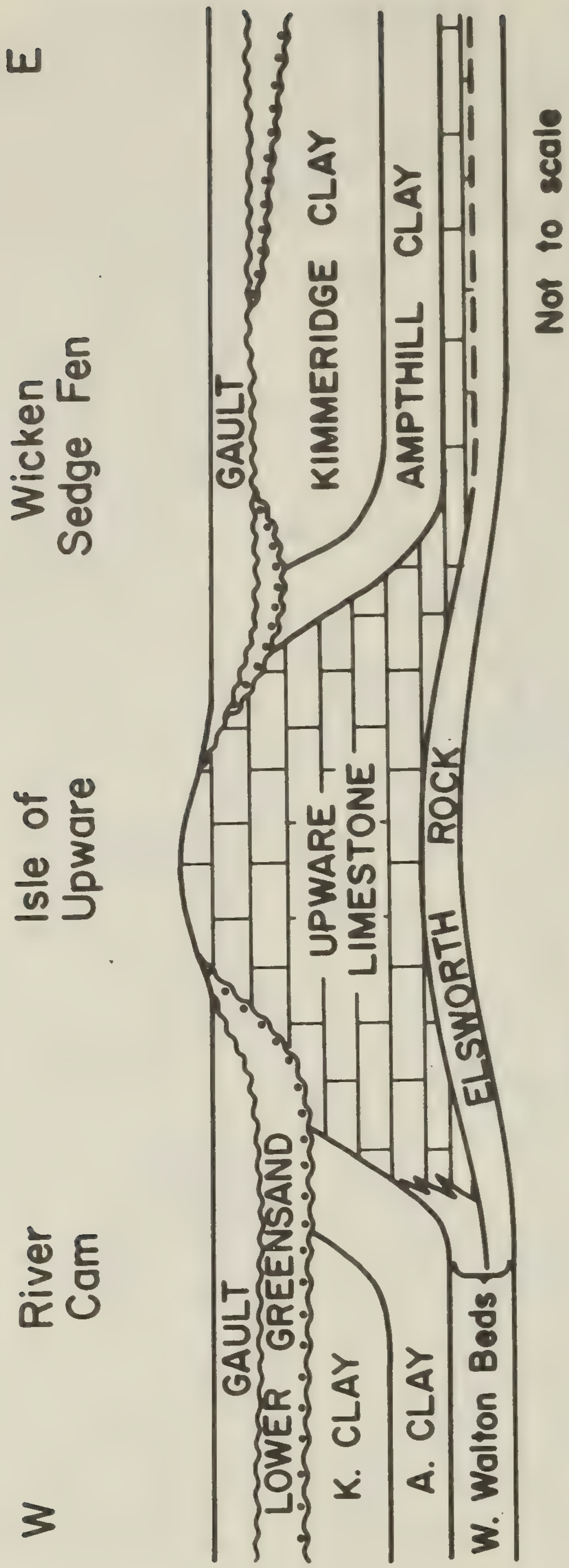
W
River Cam
Isle of Upware
Wicken Sedge Fen
E
GAULT
LOWER GREENSAND
K. CLAY
A. CLAY
W. Walton Beds
UPWARE LIMESTONE
ELSWORTH ROCK
GAULT
KIMMERIDGE CLAY
AMPTHILL CLAY
Not to scale

Fig. 4 Generalised cross-section of the Upware structure showing the stratigraphic relationships of the sedimentary units

region around Upware. They believed that granitic intrusions could be present within a metamorphic basement in adjacent West Norfolk.

The structure of the Isle of Upware has been broadly understood as a north-south axis anticline since Fitton (1836, pl.10a). This was probably based partially on observations by Sedgwick, who did not publish until 1846. Sedgwick's printed lecture notes (1861) contain a version very similar to that of Fitton. These sections show the anticline in the Corallian simply overlain by the similarly folded Kimmeridge Clay. A north-south section of the Upware ridge by Blake and Hudleston (1877) shows an east-west axis syncline with misunderstood Corallian stratigraphy and apparently conformable Lower Greensand. This was critisised by Bonney (1877) and an attempt was made to defend their original hypothesis by Blake and Hudleston (1878). Roberts (1892) put forward two possible alternative east-west sections, one invoking a fault, and the second an anticline with syncline. These needlessly complicated ideas were generated because of a supposed stratigraphic succession, that of Coral Rag overlying Oolite (see below). The east-west section of Woodward (1895, p.145) is good as far as the Corallian outcrop and subcrop is shown, but the appearance of Oxford Clay under the Gault and Lower Greensand is not correct. The section of P. Rigby (in Rastall, 1909, p.137) shows only the south part of the inlier between Upware and South Pit (Commissioners' Pit). It is basically correct, but again shows the Coral Rag and Oolite as successive units. In the very generalised sections of King and Nicholson (1946, Figs. 1-3) the Corallian is shown as a lateral equivalent of the Ampthill Clay.

Worssam (in Worssam and Taylor, 1969, pl.3) showed that Upware lies on a NNE/SSW anticlinal axis that was active in both late

Jurassic and early Cretaceous times. This was named the Upware anticline and is the most significant of a number of parallel minor fold axes in the region. Dips that have been seen in the Upware Limestone appear to radiate from this axis, however many are probably depositional. If there was a minor embayment in the west of the reef, this could account for the apparent east-west syncline recognised by Blake and Hudleston (1877). Subsequent clay deposits of the Ampthill and Kimmeridge Clays were deposited on top and draped over the relict structure, which did not compact as readily as the adjacent argillaceous deposits. The draping was enhanced by subsequent folding. In late Jurassic and Lower Cretaceous times the limestone was probably partially exhumed by erosion. Erosion of the region took place near the Jurassic-Cretaceous boundary when there was widespread uplift and sea level oscillation in southern and eastern England (see Rawson and Riley, 1983). In the Aptian, the Upware reef was definitely exhumed, probably as an island or shoal structure against which the Lower Greensand deposits were laid. After a further break in sedimentation and slight unconformity, the Gault Clay was deposited over the lower Greensand and Upware Limestone.

Upware Limestone

The Corallian rocks of Upware first attracted the attention of Fitton (1836) and Sedgwick (1846). The first detailed descriptions were those of Blake and Hudleston (1877), although their faunal listings were taken from the manuscript work of Roberts whose results were published posthumously in 1892. A further very thorough study was made by Wedd (1898) and reviews by Woodward (1895) and Arkell (1933). Since then a number of observations have been made, but the most important is the major review and reinterpretation by Gallois and

Cox (1977). Ideas expressed in the current work represent modifications of that excellent article. The limestone was first termed 'Upware limestone' by Seeley (1861), and then appeared more formally as 'Upware Limestone' in Seeley (1869, p.2). Because of its isolation from other Oxfordian limestones in Oxfordshire and Yorkshire, there was always some doubt as to where to place this limestone stratigraphically. Seeley (in Morris *et al*. 1872) believed that its age was Kimmeridgian and that it was underlain by Ampthill Clay - this appears to be a misinterpretation of the relationship at the western edge of the outcrop which dips westward and under the Ampthill Clay, and not eastwards as is the general dip of the region.

The age of the Upware Limestone is based on ammonites. These have been found principally in the pelmicrite facies (see below). Clays (1.37m thick) below have provided ammonites of the *Quenstedtoceras mariae* Zone of the Oxford Clay. These are followed by clays and ferruginous limestones (4.48m thick) belonging to the *Cardioceras cordatum* Zone of the Elsworth Rock (Arkell, 1937b), but it is important to note the Elsworth Rock of Elsworth ranges up to the *tenuiserratum* Zone (Callomon in Cope *et al*. 1980, p.3). The Upware Limestone was placed in the Tethyan perisphinctid Zone of *Gregoryceras transversarium* Zone by Spath (1933). Arkell (1937a, 1937b) preferred to place it in the *Perisphinctes plicatilis* Zone. Callomon (1960) refined Arkell's zonation and after reviewing the ammonites, believed that the Upware ammonite assemblage represented the *P. antecedans* and *P. parandieri* Subzones of that Zone. The *P. parandieri* subzone was later placed by Callomon in the overlying *G. transversarium* Zone (Torrens and Callomon, 1968). But the perisphinctid zonation has been replaced in the works of Sykes and Surlyk (1976) and Sykes and

Callomon (1979) with a more widely applicable sub-boreal zonation based on cardioceratids. The former *plicatilis* Zone approximates to two zones, a lower *C. denseplicatum* Zone and an upper *C. tenuiserratum* Zone. From the collections in the Sedgwick Museum, *Cardioceras (Subvertebriceras) densiplicatum* Boden (SMC J52897) alongside more common *C. (Cawtoniceras) cawtonense* (Blake and Hudleston) and *C. (Maltoniceras) maltonense* (Young and Bird) are typical of the *maltonense* Subzone. One good specimen of *C. (Miticardioceras) tenuiserratum* (Oppel) (SMC J13200, from Bridge Pit South) and another identified as cf./aff. *tenuiserratum* (SMC J41889, from Bridge Pit North) are typical of the *tenuiserratum* Zone (J.H. Callomon determinations). Unfortunately the precise horizon of these specimens is unknown. However it is interesting to note that most of the ammonites found recently in Bridge Pit North, represent working of the lower beds, and indicate the *maltonense* Zone. Earlier collections from the same site include specimens presumably from higher stratigraphic levels and include *tenuiserratum* Zone species. Gallois and Cox (1977, p.225) believed that the ammonites represent the *maltonense* Subzone, but in their Figure 2, they indicate that the ammonite assemblage ranges from *maltonense* to *blakei* Subzones. Wright (in Cope *et al*. 1980) places the assemblage in the upper part of the *densiplicatum* Zone and the lower part of the *tenuiserratum* Zone. (A well preserved specimen of *C.* (*Miticardiocerus*) *tenuiserratum* (Oppel) (Sedgwick Museum J.13200) came from Bridge Pit South, while another (SMC J.41889) identified as *C.* (*M*) cf./aff. *tenuiserratum* came from Bridge Pit North.) Above the Upware Limestone lies the Ampthill Clay in sharp contact. This has been seen in the west face of Bridge Pit South, but it is no longer visible (Earp and Holmes in Worssam and

Taylor, 1969). In many early accounts (e.g. Fitton, 1836; Rastall, 1909) Kimmeridge Clay is reported overlying the Corallian, but this is actually Ampthill Clay. The situation is clearly shown in the Geological Survey 1" Cambridge Sheet (1965) geological map and section.

The limestone is estimated to be about 17m thick (Gallois and Cox, 1977). At present up to about 7m are visible in the largest exposure at Bridge Pit North, and about 3m in the Commissioners' Pit, but it is not possible to correlate between them. Much of the limestone exposed today is predominantly pelmicrite (oolite of early works), though ooliths, small oncoliths and bioclastic debris are present. The celebrated coral-rich Rag of early works only makes up a small amount of the present exposures; this appears as bioclastic debris which is associated with in situ corals. In the past it was frequently attempted to separate these two lithologies stratigraphically, into an upper Rag (with corals) and a lower Oolite (Blake and Huddleston, 1877). However Wedd (1898) and Fearnsides (1904) showed that the Rag also occurred at the base of the Upware Limestone near the hamlet itself, and closely overlay the Elsworth Rock. The two lithologies are not simple stratigraphic units, but facies types. They are laterally discontinuous, either wedging out or passing laterally into each other (Brighton, 1938; Forbes, 1960; Ali, 1983, Fig. 1). The faunas associated with these two facies are usually distinctive and a summary of their distribution is given in Appendix 2. An idealised cross section of the Upware reef is given in Figure 5.

1. Pelmicrite Facies [= Oolite]: Usually it is poorly consolidated, containing some ooliths, small oncoliths and is poorly bedded. These

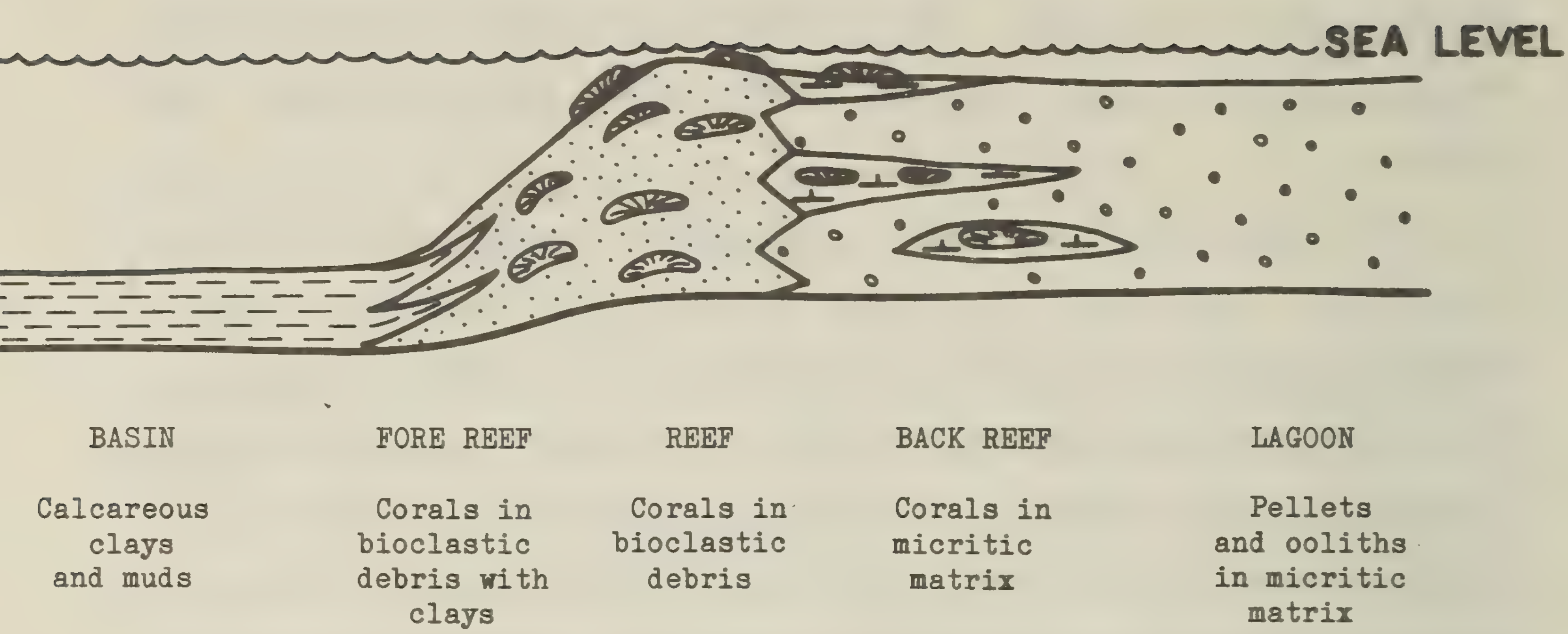
SEA LEVEL
BASIN
Calcareous clays and muds
FORE REEF
Corals in bioclastic debris with clays
REEF
Corals in bioclastic debris
BACK REEF
Corals in micritic matrix
LAGOON
Pellets and ooliths in micritic matrix

Fig. 5 Generalised distribution of facies in the Upware Limestone

pelmicrites have abundant echinoids, mainly *Nucleolites* and *Holectypus*. A number of bivalves occur usually as empty moulds, including *Gervillia, Opis, Anisocardia, Pleuromya* and *Goniomya*. The assemblage corresponds broadly but not precisely with the substrate/facies type 8 of Fürsich (1976).

2. Reefal Facies [= Rag]: Dominated by corals in either a bioclastic or a micritic matrix. There is much *in situ* growth of *Isastraea, Montlivaltia* and *Microsolena*. These are commonly bored containing the 'wormlike' trace fossil *Trypanites* and the flask-shaped *Gastrochaenolites*, the latter commonly containing the boring bivalves *Lithophaga, Gastrochaena* and *Gastrochaenopsis*. Many of these borings show clear geopetal cavities partially filled by sediment and sometimes drusy calcite. Another common, but hitherto unrecognised occupant of the borings is the bivalve *Hiatella (Pseudosaxicava)*. It appears to be a nestler, and frequently is far smaller than the boring

in which it occurs. This mode of life has been described by Kelly (1980) for other late Jurassic examples of this genus. Cemented epifauna is also common, including Liostrea and Nanogyra, both with shell preserved, and Plicatula as partial moulds because only the inner aragonite shell is dissolved leaving the outer calcite shell. Calcareous worm tubes also occur, some of which are infested by the hydrozoan Protulophila gestroi in the manner described by Scrutton (1975). There is a rich assemblage of associated byssally nestling bivalves, especially Barbatia, Eonavicula and Chlamys. These would have been living attached under overhangs and in crevices around the calcareous skeletons of the living and dead corals. The broken fragments of the skeletons of this assemblage would make up the bulk of the surrounding bioclastic sediment. There is also a common vagile epifauna comprising mainly neritid gastropods. The large tuberculate spines of Paracidaris are common. This assemblage falls clearly into the substrate/facies type 3 of Fürsich (1976).

The reefal facies with bioclastic debris may indicate marginal regions of the reef adjacent to deeper water (see Fig. 5). The turbulent environment gave a continual beating to the assemblage and the bioclastic debris accumulated around the more robust coral skeletons by both mechanical and biological breakdown. Interdigitation of clay of probable West Walton Beds clay facies may indicate fore-reef conditions. This is probably seen at Commissioners' Pit (see below). Fine-grained and micritic material was usually removed by winnowing from the coarser facies. The coral-micrite association may represent the more protected central and inner part of the reef itself where micrite is not winnowed away. The pelmicrite facies may then represent the more protected lagoonal facies with constant reworking particularly by burrowing echinoids, crustaceans and bivalves to destroy the bedding. All facies appear to be fully marine and there are no indications of emergence or proper hardground formation, although Ali (1983) does record stromatolitic crusts on Microsolena. It is possible that the reef facies may occur principally near the present western margins of the Upware Limestone outcrop. However it is here that the main quarries have been dug, where limestone was most easily quarried in former days and then transported by barge. The modern exposure of Bridge Pit North suggests this interpretation. Corals and bioclastic debris occur in the west face and lenses of corals in micritic matrix in the otherwise pelmicrite facies of the rest of the quarry. But it would be necessary to confirm this by detailed field mapping over the rest of the outcrop.

Kent (1947, p.17) has suggested that the Corallian at Upware represents part of a fringing reef on the north side of the London Platform. Boreholes from Lakenheath northwards have not encountered significant limestone facies. In his cross sections, Kent shows the Corallian rocks overstepped to the south east by the Lower Greensand mid-way between Culford and Southery. It is therefore likely that early Cretaceous erosion may have removed most of the limestone facies and only at Upware is it exposed today. Significant traces of limestones are however known from borings (Earp, Holmes and Worssam in Worssam and Taylor, 1969) at Bottisham Fen, due south of the Upware inlier, from which Paracidaris has been found, and from borings at Soham, east of the Upware inlier, where the presence of small oncolites and a Rhaxella limestone suggest an attenuated extension of the lagoonal facies. To the west of the Upware inlier at Dimmock's

Cote (only 700m west of Bridge Pit North), a boring went through 33m of blue clay including the Ampthill Clay, on 3m of rock with sand. This suggests that the reef facies dies out very rapidly westwards, or that the dip is quite steep. As Upware is the only visible exposure of reef facies between Oxfordshire and Yorkshire, it is tempting to consider that reef development only occurred when the water was sufficiently shallow, warm and well oxygenated, and that the West Walton Beds clays represent deeper, colder water conditions.

Several authors have commented on the Tethyan aspect of the Upware Limestone faunal assemblage. The ammonites include mainly a mixture of Boreal cardioceratids and Tethyan perisphinctids. Recently specimens of oppelids Ochetoceras (Campylites) henrici (d'Orbigny) (SMC J68916) and O. (Trimarginites) arolicum (Oppel) (SMC J68503) were found in Bridge Pit North. Ochetoceras is also recorded from the Elsworth rock of St. Ives and Elsworth (Arkell, 1937b), but not from anywhere else in the British Isles. However it is particularly common in the continental Oxfordian and is well known as far north as Normandy. The corals must indicate warm shallow water and include a rich variety of species, most of which are well known in Tethys, and elsewhere in England in the coral bearing Corallian facies (see Negus and Beauvais, 1979). An exception is Microsolena, which although common in Continental Kimmeridgian reefs, in England is only known from the Corallian in Yorkshire and Upware (Ali, 1983). The bivalves tend to be more cosmopolitan but include a number of genera most typical of limestone facies, in particular Isoarca, Barbatia, Eonavicula, Gervillella, Lopha and Opis. Isoarca is particularly unusual elswhere in the English Corallian together with some species of Opis. Both these genera are very typical Tethyan forms (Arkell, 1929). A new record to this country is a single specimen of Pulvinites rupellensis (d'Orbigny) (SMC J5179) which is particularly common in the Lower Kimmeridgian Couches à Montlivaltia near La Rochelle, France, and which is so far the only recorded true Oxfordian example (T. Palmer, pers. comm. 1983).

Lower Greensand

The Lower Greensand is unfortunately poorly exposed today, in comparison to the middle of the last century when Coprolite working was a major local industry (see Grove, 1976, for a popular account). Early geological studies of the deposit at Upware include Walker (1867); Teall (1873); Bonney (1875); Keeping (1881), but the most important remains the mainly palaeontological study of Keeping (1883). The Lower Greensand normally rests unconformably on Kimmeridge Clay in the region, but in the core of the anticlinal structure of Upware this has been eroded away and the Lower Greensand rests directly on the Upware Limestone. At Upware the Lower Greensand reaches a thickness of about 3m, and is composed of sands with clay and silt, and containing the once economic conglomerates of reworked phosphatic material, with lydites and quartzose pebbles. There is one principal conglomerate at the base, and a second at some distance above it.

The phosphatised nodules and pebbles are well rounded, the types have been discussed by Keeping (1881) and include sandstones, shales, cherts, pitchstone, fossiliferous Palaeozoic rocks as well as late Jurassic fossils. Of particular interest are some of the phosphatised sandstones which contain the distinctive bivalve Dicranodonta vagans (Keeping, 1883). These are perhaps all that remains of the late Jurassic-early Cretaceous Sandringham Sands (Fig. 2) which at present outcrop south east of the Wash and which wedge out southwards near

Southery, where they are in eroded contact with the Carstone. The presence of this bivalve, which is only known in situ from rocks of Middle Volgian to early Upper Ryazanian age (Kelly, 1984), indicates the possible former presence in the Upware area of Sandringham Sands.

The indigenous fauna of the Lower Greensand was particularly rich in brachiopods. Casey (1961) gives a summary of the palaeontology. He has demonstrated that the Lower Greensand of the Upware region contains ammonite faunas of derived Lower Aptian and indigenous Upper Aptian age. In early Aptian times there was still no direct sea-link across central England, and it was only in Upper Aptian times that an open strait formed. Once formed, it lasted throughout the rest of the Cretaceous (Middlemiss, 1962b, Figs. 1-3). The nature of the deposits indicate that in Upper Aptian times central England was a shallow strait with shifting sands and scouring currents. Middlemiss (1962a; 1962b) recognised an Upper Aptian brachiopod fauna from Upware which represented a nearshore assemblage of the London Platform comparable to similar fauna from the Bargate beds on the south side of the platform. Schwarzacher (1953) has suggested NE-SW current directions from his work on sands in west Norfolk. However his observations were based on deposits now believed to be Valanginian (Leziate Member of the Sandringham Sands). His postulated land mass to the north-west lies in the middle of what is now considered to be the Spilsby Basin; the land lying to the south east was the London Platform.

The Lower Greensand of Upware does not appear to have been analysed petrographically, but from nearby Ely, Rastall (1919) records the following heavy mineral assemblage; zircon, tourmaline, kyanite, staurolite and rutile.

Gault

The Gault was originally recorded exposed near Upware by Keeping (1868). Unfortunately it is no longer exposed. However during the erection of pylons across the Isle of Upware in the 1960's, the excavations were examined by Dr. C.L. Forbes and produced some Gault, some of probable *Hoplites dentatus* Zone, Lower Albian age. This information forms part of Appendix 1. A detailed synthesis of the Gault in East Anglia is given by Gallois and Morter (1982).

Details of Exposures

The Geological Society of Norfolk excursion was planned as a north-south traverse of part of the Isle of Upware. The party assembled in the centre of Upware itself and then followed the path at the back of the marina northwards along the edge of the fenland. To the west dark peaty fenland soil could be seen in the flat, low-lying ground. To the east the ground rises sharply and the soil becomes paler and more brownish, with common fragments of limestone, many of which are broken fragments of corals. This is the distinctive brown calcareous soil which is restricted to the Corallian outcrop (Hey and Perrin, 1960) and was first recognised by Vancouver (1794). The footpath turns right at a ditch and then left onto Fodderfen Drove. Within the trees to the left lies the Commissioners' Pit and the small canal from the river along which barges transported the quarried products of the pit. The quarry can be entered from the drove near the north east corner.

Locality 1

Commissioners' Pit [= South Pit of the older literature], 0.8 km NE of the T-junction at Upware (TH 539708). It is now a largely overgrown nature reserve owned by the Cambridgeshire Education Department, who have recently cleared some of the north east face of the quarry as a geological site. About 1.3m of well-bedded, bioclastic, coral-rich limestone with some clays overlies about 1m of pelmicrite. The bedding does not show a clear dip and it undulates, as there appears to be compaction of clays especially around coral heads. This is at present the clearest exposure in the area of the reef facies of the Upware Limestone. The presence of clays suggests the close proximity of the basinal clays of the West Walton Beds, and therefore this locality represents the outer margin of the reef with the fore-reef facies. The sequence is as follows:

1.50m	Rubbly weathered limestone and soil
.25	Micritic limestone with tabular coral
.04	Brown clay
.25	Micritic to bioclastic limestone with large calcite replaced coral head of *Isastrea* (1m wide and .15m high). Common moulds of *Montlivaltia* in growth position
.40	Micritic and bioclastic limestone with *Microsolena* at base, with borings of *Lithophaga*; *Plagiostoma*
.04	Brown clay seam draped over and interrupted from below by coral head
.30	Shelly detrital limestone with *Isastrea*, *Microsolena*, *Plicatula*, *Lithophaga*, pectinids, *Opis*, *Paracidaris*
1.00+	Pellety micritic limestone with ooliths and few body fossils.

Clay residues from the limestone associated with the corals have given a smectite content of 88-98%, illite 2-12% and kaolinite <2%. This is believed to have been formed by the breakdown of contemporary volcanic material (Ali, 1977), perhaps from the North Sea region.

According to A.G. Brighton (pers. comm. 1983) the southern face of this pit used to expose the Lower Greensand and the Gault. No trace of these can now be seen.

In the field immediately to the north of Commissioners' Pit there are traces of old workings, probably those of the Coprolite workings from the middle of last century. The field is private property, belonging to Mr. F.S. Fuller of Upware. In this field is a recent excavation.

Locality 2

Recent small excavation for hardcore (TF 53967100), with access via gate from Fodderfen Drove. The excavation shows about 2m of weathered rubbly Corallian Limestone, mainly irregular to subrounded fragments of pisolitic micrite. In the upper 1m are scattered lyditic and phosphatic rounded pebbles up to 3 cm diameter, some concentrated in lenses, but otherwise not clearly bedded. Some pebbles show traces of Chondrites type burrows which must predate the original cementation of the concretion, and the outer surface of many are bored, some showing Gastrochaenolites. One pebble was the eroded mould of a body chamber of perisphinctid ammonite, another the internal mould of Pleuromya. These pebbles represent the base of the Lower Greensand. However it is not clear whether they are in situ, as originally in the Lower Cretaceous, or whether the whole deposit has been churned up by periglacial activity or even during the extraction of coprolites. The base of the soil above the weathered limestone is very rich in clay and the Lower Greensand pebbles, and these latter may represent washings from the coprolite workings. If this material is in situ, then it represents the reworking of Corallian limestone into the base of the Lower Greensand in Aptian times. This would then be the nearshore deposit first recognised by Keeping (1881). Returning to the drove via the gate, the leader pointed out the succession that had been observed when the pylons that traverse the Isle of Upware were constructed (see Appendix 1). The highest ground to the east is composed of the Upware Limestone and as one goes downhill towards the River Cam to the west one traverses first the Lower Greensand in the area of the drove and then in the lower ground of the adjacent field beyond the old workings there is the Gault Clay, and then Fenland deposits. Seeing this topographical relationship it is easy to envisage the Lower Greensand sea actively eroding the projecting mass of Upware Limestone.

Locality 3

A number of modern animal burrows at the edge of the Fodderfen Drove between the two slight bends (TF 54057115-54107120) have thrown up much sandy and pebbly material from the Lower Greensand. It is not possible to say whether these have come from in situ or from old dumps from the coprolite workings. However they produced two brachiopods, part of a large Terebratula and a Terebratulina. There were also some large blocks of calcite-cemented glauconitic sandstone with further conglomeratic clasts.

The party proceeded further north along the drove to where it is crossed by Dimmock's Cote road. On the south west of the cross roads is the largely infilled Bridge Pit South (TF 542721). A face is visible, although partly obscured by rat-infested garbage, and the site was not examined further. To the north east of the cross roads is the currently worked Bridge Pit North.

Locality 4

Bridge Pit North (TF 542721) is worked by the Euston Lime

Company. The working floor of the pit is approximately 200m square. The state of faces in the pit is constantly changing, but at the time

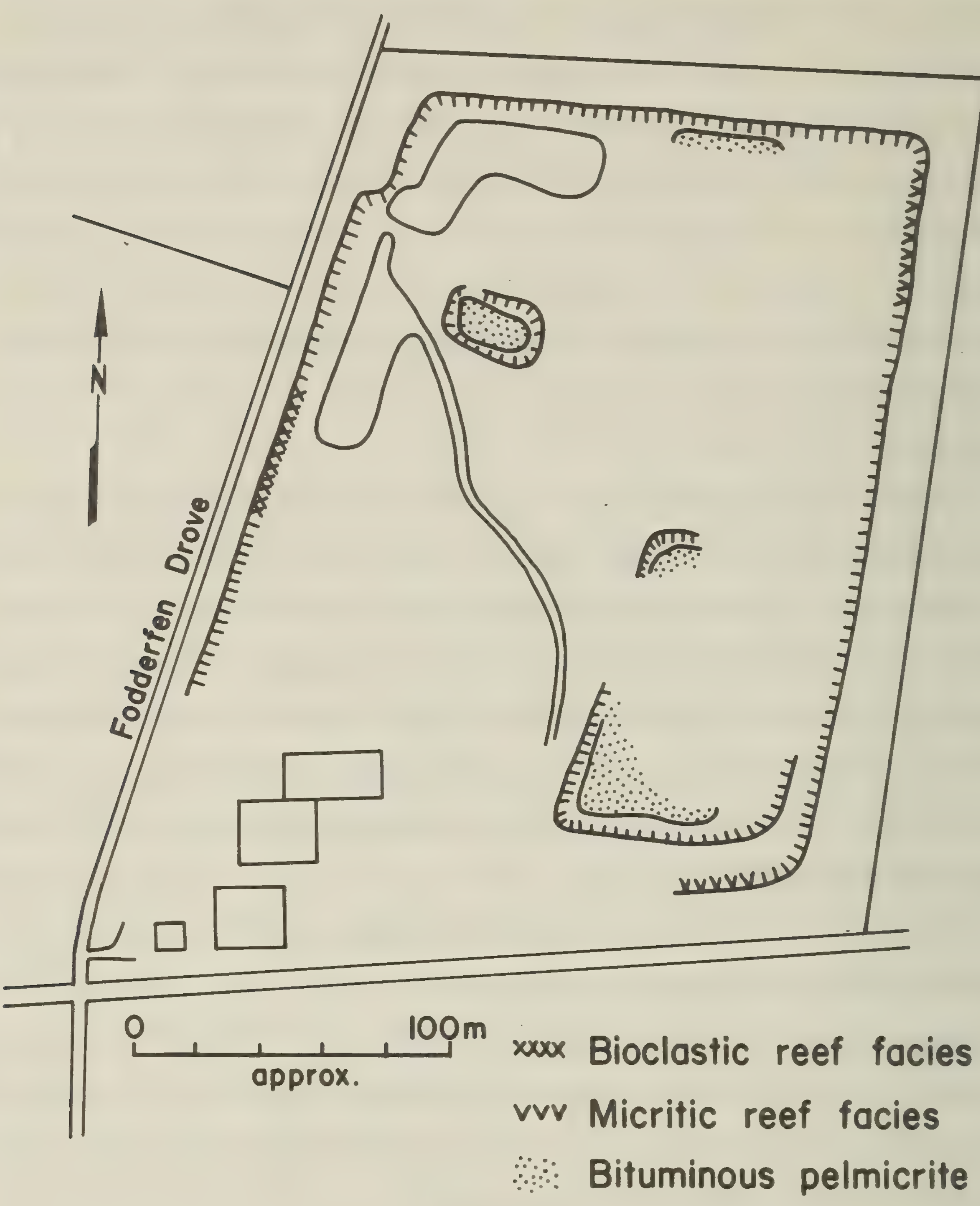
N
Fodderfen Drove
0
100m
approx.
xxxx Bioclastic reef facies
vvv Micritic reef facies
Bituminous pelmicrite

Fig. 6 Sketch map of Bridge Pit North, Upware

of the visit it was as in Figure 6. In all about 6m of Corallian is exposed in discontinuous sections. It is not possible to give an accurate measured section. Most of the strata exposed at present are in the pelmicrite facies. Bedding is not clearly seen except in the north face where an apparently regular dip of 2° west is seen over about 100m. Much of the bedding has probably been destroyed by bioturbation. In addition to the abundant Holectypus depressus (Leske) and Nucleolites scutatus (Lamarck) in calcite preservation, are common, soft bottom, usually burrowing bivalves. All the aragonite shells have been dissolved and the commonest preservation is as composite moulds. Some early cemented limestone, however, provides uncrushed moulds and casting techniques as used by Kelly and McLachlan (1980) prove very useful. The deepest parts of the pit show up to about 2m of rather blue grey, clay-rich pisolite. It is not very fossiliferous but Holectypus depressus occurs. This unit was recognised by Wedd (1898, p.604) in a well at High Fen Farm, c.1 km north of Bridge Pit North. He listed its fauna which is similar to the pelmicrite elsewhere. The colour is due largely to the clay content, but there is also a certain amount of organic material present and the rock has a strong bituminous smell. The colour may also be due to fine-grained iron pyrites in the sediment, which may become oxidised when weathered. Near the junction of the lower grey unit trace fossils can be picked out clearly. They appear to be the large branching burrows of the ichnogenus Thallasinoides which was probably constructed by crustaceans. A number of crab chelae were found in the upper pelmicrites, but were not associated with the burrows.

The main exposure of reef facies is in the middle of the west face, close to the top, although this is now largely covered by talus. It is here that the principal coral assemblage occurs today, with its associated borers, cementers and other byssate epifauna. The matrix is bioclastic.

A micritic facies with corals was described by Ali (1983) from the south face of the quarry. He records Microsolena thurmanni Koby and M. foliosa Roniewicz with other corals, all in a biomicritic lens up to 1m thick, overlain by about 0.5m of oolite and underlain by biosparite. Unfortunately this cannot be seen in situ at present, although loose specimens of Microsolena can be found at that place and also near the north end of the east face of the quarry. These are commonly encrusted by Plicatula and bored by Gastrochaena and Lithophaga. Some borings also contain Hiatella.

Acknowledgements

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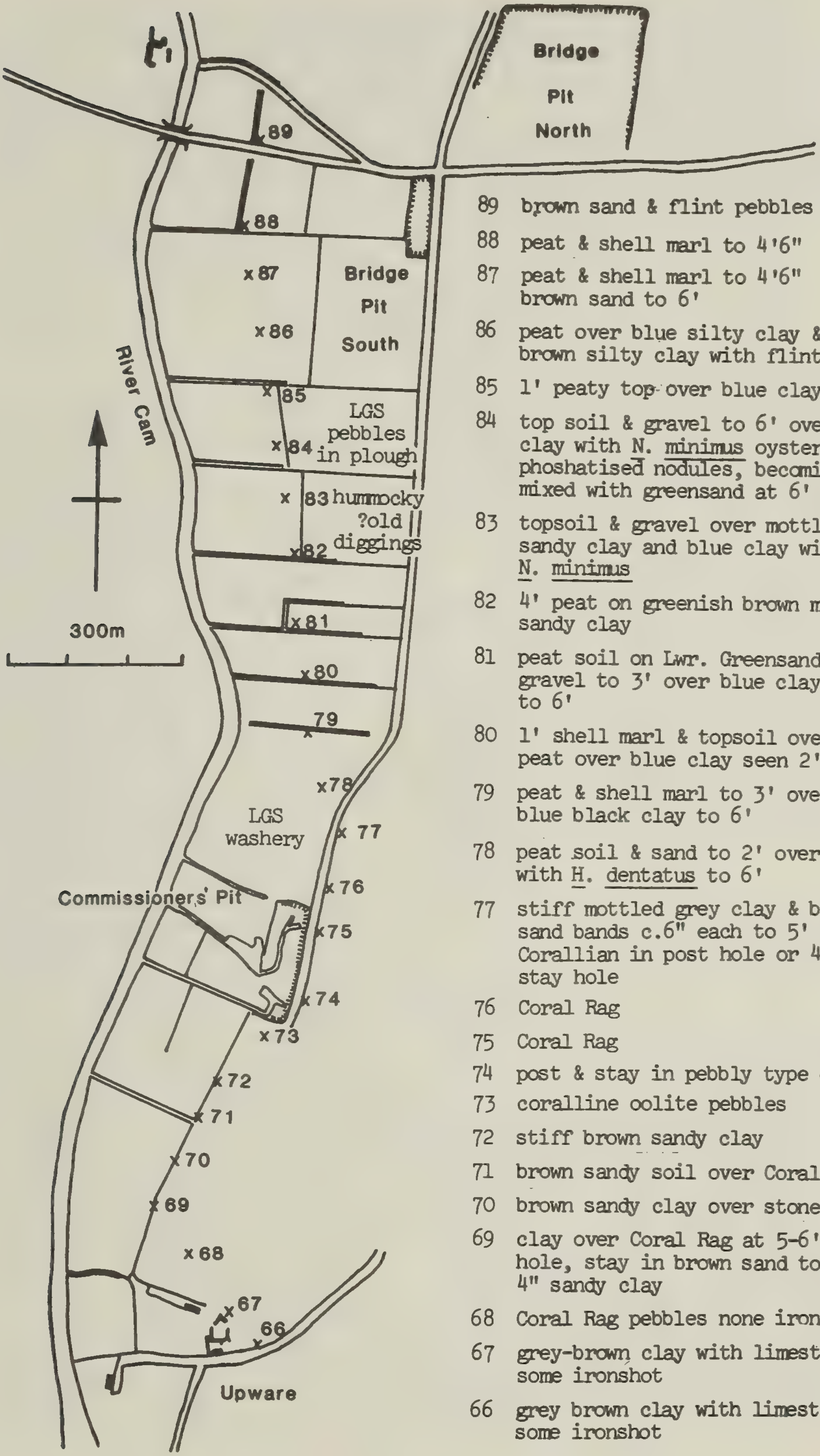
Appendix 1: Upware Pylon Sites

This sketch map (p.33) is based on the field notes of Colin Forbes (1960's) of the region between Upware and Bridge Pit North. The numerals represent pylon post holes and the observations made at these points are given on the right. Note the definite appearance of Gault Clay in Holes 78, 83 and 84, in close proximity to the Lower Greensand in 81 and adjacent fields, and the Corallian in 73-77.

Jurassic & Cretaceous of Upware


Bridge Pit North
x 89
x 88
x 87
Bridge Pit South
x 86
x 85
LGS pebbles in plough
x 84
x 83
hummocky ?old diggings
x 82
x 81
x 80
x 79
x 78
LGS washery
x 77
River Cam
Commissioners' Pit
x 76
x 75
x 74
x 73
x 72
x 71
x 70
x 69
x 68
x 67
x 66
Upware
300m

89 brown sand & flint pebbles

88 peat & shell marl to 4'6"

87 peat & shell marl to 4'6"
brown sand to 6'

86 peat over blue silty clay &
brown silty clay with flint pebbles

85 1' peaty top over blue clay to 6'

84 top soil & gravel to 6' over blue
clay with *N. minimus* oyster &
phoshatised nodules, becoming
mixed with greensand at 6'

83 topsoil & gravel over mottled
sandy clay and blue clay with
N. minimus

82 4' peat on greenish brown mottled
sandy clay

81 peat soil on Lwr. Greensand sandy
gravel to 3' over blue clayey sand
to 6'

80 1' shell marl & topsoil over 3'
peat over blue clay seen 2'

79 peat & shell marl to 3' over stiff
blue black clay to 6'

78 peat soil & sand to 2' over Gault
with *H. dentatus* to 6'

77 stiff mottled grey clay & brown
sand bands c.6" each to 5' on
Corallian in post hole or 4' in
stay hole

76 Coral Rag

75 Coral Rag

74 post & stay in pebbly type coralline oolite

73 coralline oolite pebbles

72 stiff brown sandy clay

71 brown sandy soil over Coral Rag at 6'

70 brown sandy clay over stone at 6'

69 clay over Coral Rag at 5-6' in post
hole, stay in brown sand to 4' over
4" sandy clay

68 Coral Rag pebbles none ironshot

67 grey-brown clay with limestone pebbles
some ironshot

66 grey brown clay with limestone pebbles
some ironshot

Appendix 2: Upware Limestone: Faunal and Floral List

This list is based on the collection of the Sedgwick Museum, Cambridge and the author's collecting. It is supplemented by information from Ali (1983); x = R. Goldring pers. comm. 1984; Arkell (1929-1937, 1935-1948, 1937b); Johnson (1984); Van Straelen (1925); Woods (1904). Abbreviations: p = pelmicrite facies; r = coral reef facies; x = R. Goldring (pers. comm. 1984); 1 = Arkell, 1929-1937; 2 = 'Middle Pit' in Sedgwick Museum Collection, perhaps represents Bridge Pit South; 3 = Sedgwick Museum Collection. Note that the new Pit of Arkell (1937b) is Bridge Pit North, and that his Bridge Pit is Bridge Pit South.

	N Pit	S Pit	Br S	Br N	See Note
AMMONITES					
Peris. (Dichotomosphinctes) buckmani Arkell		p	p		
P. (Dichotomosphinctes) antecedens Salfeld	p			p	
P. (Dichotomosphinctes) gresslyi de Loriol	p			p	
P. (Perisphinctes) chloroolithicus (Gümbel)		?p		p	
P. (Perisphinctes) parandieri de Loriol		p			
P. (Arisphinctes) maximus (Young and Bird)	p				
P. (Arisphinctes) pickeringius (Young and Bird)			p		
P. (Arisphinctes) vorda Arkell			p		
Asp. (Euaspidoceras) paucituberculata Arkell	p				
Card. (Cawtoniceras) cawtonense (Bl. and Hud.)	p	p		p	
Cardioceras (Maltoniceras) bodeni Maire		p			
Card. (Maltoniceras) highworthense Arkell				p	
Card. (Maltoniceras) maltonense (Y. and B.)		p		p	
Card. (Miticardioceras) tenuiserratum (Oppel)		p	p	p	
Card. (Subvertebriceras) densiplicatum Boden			p	p	
Ochetoceras (Campylites) henrici (d'Orb)				p	
Ochetoceras (Trimarginites) arolicum (Oppel)				p	
BELEMNITES					
Hibolites hastatus (Blainville)		?p			
Pachyteuthis abbrevata (Miller)		p			
BIVALVES					
Isoarca multistriata Etallon		r	r		
Isoarca texata Quenstedt		r	r		
Eonavicula quadrisculcata (J.de C. Sowerby)	r	r	r	r	
Barbatia (Barbatia) pectinata (Phillips)	r	r	r	r	
Nemodon? lanthanon (Blake and Hudleston)		r	r		
Grammatodon (Grammatodon) aemulum? (Phillips)		r		r	
Idonearca contracta (Phillips)					1
Arcomytilus pectinatus (J. Sowerby)		p		p	
Lithophaga (Lithophaga) inclusa (Phillips)		r	r	r	
Modiolus (Modiolus) bipartitus J. Sowerby	p	r		p	
Mytilus ungulatus (Young and Bird)	p	p		pr	
Pinna (Pinna) lanceolata J. Sowerby		p			
Trichites plotii Lycett		p			
Pteroperna polydon (Buvignier)		r		p	

	N Pit	S Pit	Br S	Br N	See Note
Gervillella aviculoides (J. Sowerby)		p			
Gervillella sulcata Etallon		p	p	p	
Pulvinites rupellensis (d'Orbigny)		r			
Oxytoma (Oxytoma) expansa (Phillips)					1
Isognomon (Isognomon) subplana Etallon		p		r	
Entolium (Entolium) corneolum (Young and Bird)		r			
Camptonectes (Camptonectes) auritus (Schloth.)				p	
Camptonectes (Camptochlamys) clathratus (Roemer)		p			
Chlamys (Chlamys) textoria (Schlotheim)		r		r	
Radulopecten fibrosus (J. Sowerby)	p	p		p	
Radulopecten inaequicostatus (Young and Bird)		pr		p	
Radulopecten scarburgensis (Young and Bird)		p			
Spondylopecten (Plesiopecten) subspinosa (Schlotheim)	p	p	r	p	
Eopecten spondyloides (Roemer)		pr		r	
Plicatula (Plicatula) weymouthiana Damon		r		r	
Placunopsis radiata (Phillips)		r			
Ctenostreon proboscideum (J. Sowerby)		r			
Plagiostoma laeviuscula J. Sowerby		r			
Plagiostoma mutabilis Arkell		?r			
Plagiostoma rigida J. Sowerby		r	p	r	
Plagiostoma zonata Arkell		r			
Pseudolimea alternicosta (Buvignier)		r			
Limatula elliptica Whiteaves		r			
Gryphaea (Bilobissa) dilatata (J. Sowerby)		p		p	
Nanogyra nana (J. Sowerby)		r		r	
Lopha gregarea (J. Sowerby)	r			r	
Lopha solitaria (J. Sowerby)					1
Trigonia (Trigonia) reticulata Agassiz		p		pr	
Myoconcha texta Buvignier		r		p	
Lucina rotundata (Roemer)					1
Mactromya aceste (d'Orbigny)					1
Neocrassina ovata (W. Smith)		r	p	r	
Neocrassina subdepressa (Blake and Hudlestone)		p	p		
Pressastarte nummus (Sauvage)		r		r	
Coelastarte cotteausia (d'Orbigny)		r			
Nicaniella (Nicaniella) extensa (Phillips)		r			
Prorokia problematica (Buvignier)		r			
Opis (Trigonopis) curvirostra (W. Smith)		r	r	p	
Opis (Trigonopis) corallina Damon		r			
Opis (Trigonopis) virdunensis Damon		r		r	
Opis (Coelopis) arduennensis d'Orbigny		r			
Opis (Coelopis) upwarensis Arkell		r	r	r	
Opisoma rupellensis d'Orbigny		r			
Protocardia dyonisea (Buvignier)		r			
Quenstedtia laevigata (Phillips)		r			
Quenstedtia gibbosa Hudleston		r		p	
Sowerbya triangularis (Phillips)		r	pr	pr	
Anisocardia globosa (Roemer)	r	r	p	pr	
Anisocardia isocardioides (Bl. and Hud.)					1
Gastrochaena (Gastrochaena) moreana Buvignier		r		r	
G. (Gastrochaeonopsis) recondita (Phillips)			r	r	

	N Pit	S Pit	Br S	Br N	See Note
Hiatella (Pseudosaxicava) bernardi Chavan		r		r	
Pholadomya aequalis J. de C. Sowerby					1
Pholadomya canaliculata Roemer		r			
Pholadomya protei (Brongniart)		r			
Pleuromya uniformis (Phillips)		p		p	
Goniomya literata (J. Sowerby)		p		p	
Pachymya (Acromya) rathieri de Loriol		p			
Machomya cf. *applanata* Cossman				p	
See also trace fossils					

GASTROPODS

	N Pit	S Pit	Br S	Br N	See Note
Bathrotomaria reticulata (J. Sowerby)	p	r	p	r	
Trochotoma? tornatilis (Phillips)		r		r	
Emarginula goldfussi (Roemer)		r			
Pseudofissurella corallensis (Buvignier)		r			
Proconulus? acuticarina (Buvignier)		r			
Buckmania erinus (d'Orbigny)				r	
Neritopsis decussata Münster		pr			
'Littorina' muricata (J. Sowerby)		r		p	
Amberlya princeps (Goldfuss)		r	r		
Amberlya meriani (Goldfuss)	p	pr		p	
Bourguettia saemanni (Oppel)				r	
Procerithium muricatum (J. Sowerby)		pr			
Natica clytia d'orbigny		r		p	
Natica clymenia d'Orbigny		r			
Nerinaea cf. *pseudovisurgis* Hudleston				p	
?*Alaria* sp.		pr			
Pseudomelania heddingtonensis (J. Sowerby)		pr	r	r	

SCAPHOPOD

	N Pit	S Pit	Br S	Br N	See Note
Dentalium sp.	p	p			

BRACHIOPODS

	N Pit	S Pit	Br S	Br N	See Note
Moorellina granulosa (Moore)				x	
?*Rhynchonella* sp. juv.		r			
Terebratula insignis var. *maltonensis* (Oppel)	p	r		p	

BARNACLE

See trace fossil *Rogerella*

ECHINOIDS

	N Pit	S Pit	Br S	Br N	See Note
Rhabdocidaris sp.				p	
'Cidaris' smithii (Wright)		r		r	
Paracidaris florigemma (Phillips)		r		r	2
Pygaster umbrella (Agassiz)	p		p		
Hemicidaris intermedia (Fleming)	p	?		p	
Pseudodiadema hemisphaerica Agassiz			p		

	N Pit	S Pit	Br S	Br N	See Note
Diplopodia versipora (Woodward)	p	p		p	
Stomechinus gyratus (Agassiz)		p		p	
Glypticus hieroglyphicus Goldfuss		p			
Holectypus depressus (Leske)	p	p	p	p	
Hyboclypus gibberulus Agassiz	p	p	p	p	
Pygurus pentagonalis (Phillips)				p	
Nucleolites scutatus (Lamarck)	p	p	p	p	
Collyrites bicordata (Leske)	p	p		p	
Desorella elata (Desor)		p			
CRINOIDS					
Apiocrinus polyplocus (Merian)		r		p	
Isocrinus sp.	p	p	p	p	
Millericrinus echinatus Goldfuss		r			
See also trace fossil *Trypanites*					
ANNELIDS					
Glomerula gordialis (Schlotheim)		r			
Serpula deplexa Phillips		r	p	r	
Serpula sulcata (J. Sowerby)		r		pr	
Fine planispiral form		r			
Trochispiral with annulations		r			
See also trace fossil *Terebripora* sp.					
BRYOZOANS					
Stomatopora sp.				x	
Undetermined					3
CRUSTACEANS					
Gastrosacus carteri Van Straelen		?r			
Glyphaea sp.	?	pr		p	
Prosopon marginatum Meyer		r			
See also trace fossil *Thalassinoides*					
CORALS					
Fungiastraea arachnoides (Parkinson)		r		r	
Isastrea explanata (Goldfuss)		r		r	
Microsolena thurmanni Koby		r		r	
Microsolena foliosa Roniewicz				r	
Montlivaltia dispar Phillips		r		r	
Rhabdophyllia phillipsi (Edwards and Haime)		r			
Thamnasteria concinna (Goldfuss)		r	r	r	
Thecosmilia annularis (Fleming)		r			
Stylina tubifera (Phillips)		r			
HYDROID					
Protulophila gestroi Rovereto		r			

	N Pit	S Pit	Br S	Br N	See Note
SPONGES					
Enaulofungia floriceps (Phillips)				x	
Holcospongia glomerata (Quenstedt)		r	r	r	
Rhaxella perforata (Hinde)				x	
See also trace fossils					
TRACE FOSSILS					
Gastrochaenolites sp. (Bivalve borings in coral)		r		r	
Rogerella sp. (Cirrepede borings in *Trichites*)				p	
Cliona sp. (Sponge borings in corals)				r	
?*Terebripora* sp. (Bryozoan borings in bivalve)				r	
Thalassinoides sp. (Crustacean burrows in pelmicrite)				p	
Trypanites sp. (?Annelid borings in corals)		r		r	
ALGAE					
Girvanella sp.				x	
Stromatolite				p	
WOOD					
Undetermined				p	

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NOTES ON CHALK FOSSILS:

Whittlesea, P.S.*

1. **Note on a temporary section at Bramerton, near Norwich**

During late September 1983 a trench was dug for sewage pipes across Bramerton Common. It ran from the extreme eastern end of the Common (TG 297061) to about 100 metres west of the Woods End public house. The trench was dug in Chalk throughout its length. A second trench was dug along the road on the west side of the Common up the hill towards Surlingham and intersecting the first at the bend in the road (TG 295061). No Chalk was visible in this trench. The Chalk in the first trench was waterlogged, being close to the river, and very little information could be gained by examining it _in situ_. Material excavated from the eastern end of the Common was dumped in a clearing in the woods behind the Common. After it had had a chance to dry out several features of interest could be seen: the Chalk was markedly yellow, with abundant marly streaks, these being the trace fossil _Zoophycos_, and perpendicular to these, but not intersecting them, were frequent tubular burrows about one centimetre thick and several centimetres long. Much of the Chalk had obviously come from a hardground and contained many sponges (_Ventriculites_ spp., _Coscinopora_ spp., _Micropora_ spp., etc.) and baculitid ammonites, together with moulds of bivalves and gastropods. Flints were generally common.

Careful searching of the excavated Chalk produced six belemnites, all of which were referable to the Campanian genus _Belemnitella_. A list of the species found is given below.

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* 8 Eaton Old Hall, Hurd Road, Eaton, Norwich NR4 7BE

Faunal list

Porifera
Ventriculites infundibuliformis (S. Woodward)
Coscinopora quincunxialis T. Smith
Entobium cretacea (Portlock)
Aphrocallistes cylindrodactylus Schrammen

Coelenterata
Axogaster spp.

Brachiopoda
Ancistrocrania parisiensis (Defrance)
Carneithyris subcardinalis (Sahni)
Neoliothyrina obesa Sahni
Cretirhynchia arcuata Pettitt
Cretirhynchia norvicensis Pettitt
Magas chitoniformis (Schlottheim)

Bivalvia
Pycnodonte vesicularis (Lamarck)
Spondylus latus (Sowerby)
Spondylus spinosus (Sowerby)
Chlamys cretosus (Defrance)
Pecten trigeminatus (Goldfuss)
Atreta nilssoni (von Hagenow)
Margostrea alaeformis (Sowerby)
Neithea sexcostata (Woodward)
Plagiostoma cretacea Woods
Gyropleura inequirostrata (Woodward)

Echinodermata
Cidaris sp.
Phymosoma konigi (Mantell)
Echinocorys sp.
Galerites abbreviatus (Desor)
Austinocrinus bicoronatus (von Hagenow)
Bourgueticrinus sp.

Annelida
Sclerostylus macropus (Sowerby)
'Serpula' contracta (Sowerby)
Neomicrorbis crenatostriatus (Munster)
Placostegus sp.

Cephalopoda
Belemnitella mucronata (Schlottheim)
Belemnitella langei sensu Birkelund non Jeletzky
Baculites sp.

Bryozoa
Membranipora scalprum Brydone
Membranipora furina Brydone
Membranipora palpebra Brydone
Dionella trifaria (von Hagenow)
Callopora sp. nov. (?)
Onychocella inelegans (Lonsdale)
Aechmella anglica (Brydone)
Homalostega punctilla Brydone
Pliophloea cornuta (von Hagenow)
Leptocheilopora magna Lang
Porina goldfussi Brydone
Cryptostoma corallinum Brydone
Diastopora spp.
Stomatopora irregularis (Hennig)
Idmonea sp. nov. (?)
Actinopora brogniarti (Edwards)
Disporella irregularis (d'Orbigny)

Omitted from this list is a considerable suite of undescribed forms (mostly bivalves) represented only by their paired internal and external moulds, and some unidentified bryozoa.

Reference

Wood, C.J. 1967. Some new observations on the Maastrichtian stage in the British Isles. Bull. geol. Surv. G.B. 27, 271-288.

2. Occurrence of the Brachiopod Kingenella kongieli Popiel-Barczyk in the Norwich Chalk

Thorough collecting from St. James' Hollow, Heathgate, Norwich produced a variety of brachiopods. Amongst these was a small terebratulid, which, on careful examination including a dissection of the brachidium, proved to be a specimen of Kingenella kongieli Popiel-Barczyk.

Kingenella was originally described from the Upper Maastrichtian of Nasilow, Poland by Popiel-Barczyk (1968). This is the first undoubted British record of the genus.

Whittlesea

Once the specimen from St. James' Hollow was identified the author re-examined similar material in his collection in the hope of finding further examples. Two more specimens were found in the author's collection of material from the Lower Maastrichtian of Sidestrand, North Norfolk. Subsequent collecting produced another five specimens from this locality.

The specimens from both localities show traces of what originally must have been a well developed spicular skeleton; a feature not recognised in the material that Popiel-Barczyk had available.

Kingenella may be distinguished (using external features) from *Kingena* by its lack of a pustulose ornament; from *Magas* by having more punctae per millimetre square; and from juvenile *Carneithyris* by the presence of a much longer median septum in the brachial valve.

List of Material Examined

Author's Collection and Catalogue Numbers

SJH90/1
Complete specimen, both valves now disarticulated and cleaned. Senonian, Campanian, zone of *Belemnitella mucronata*, Saint James' Hollow, Heathgate, Norwich.

SS181/1/1-7
Seven specimens, two complete, the rest damaged to varying degrees. Lower Maastrichtian, zone of *Belemnella lanceolata*, Sidestrand (glacial erratic), North Norfolk.

Reference

Popiel-Barczyk, E. 1968. Upper Cretaceous Terebratulids (Brachiopoda) from the Middle Vistula Gorge. Prace Muzeum Ziemi, No.12, 1968.

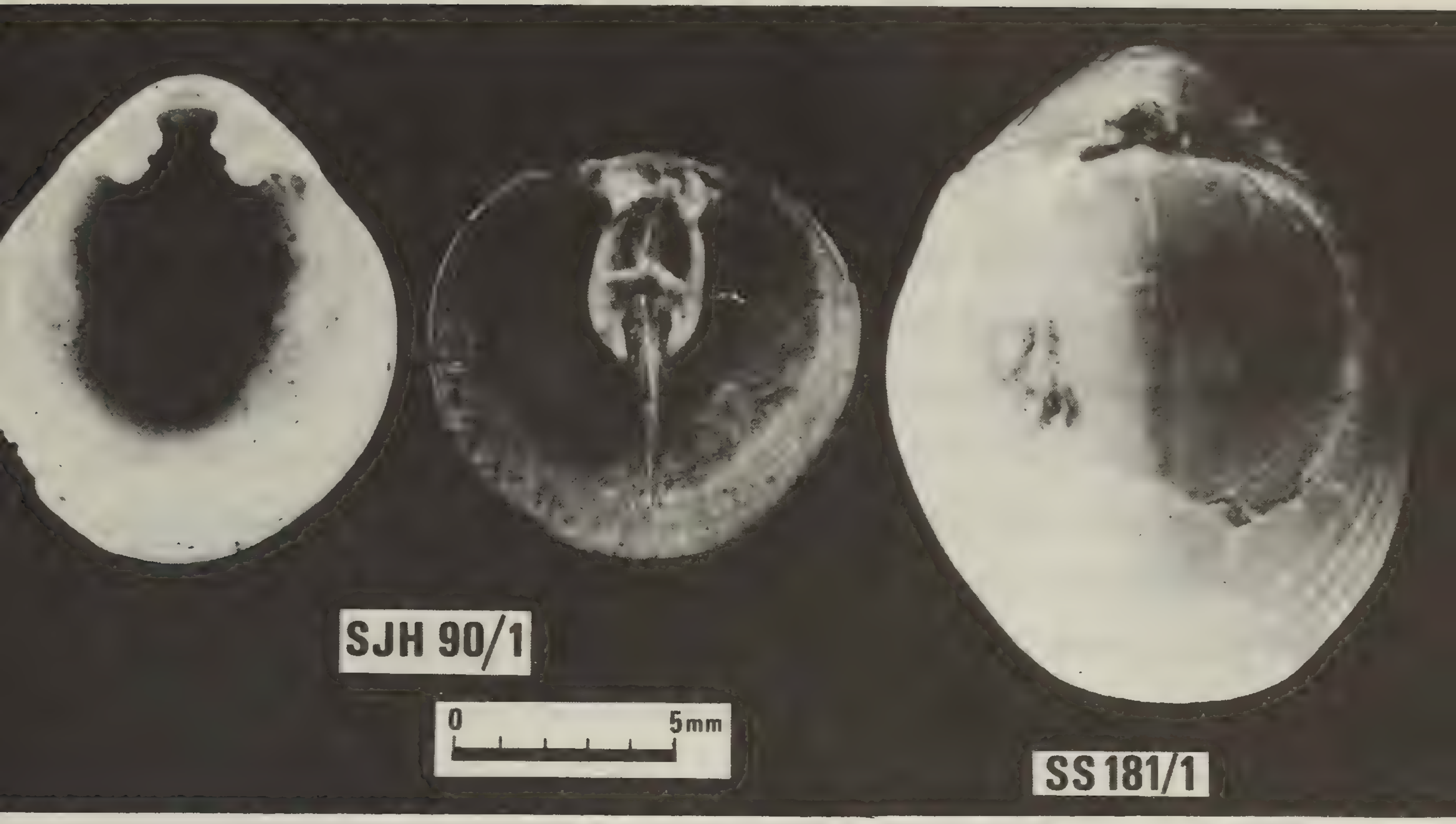

Fig. 1 Kingenella Kongieli Popiel-Barcyck

3. Preliminary Account of a Bryozoan - "Algal" Association from the Upper Campanian and Maastrichtian of Norfolk

Voigt (1981) described a bryozoan - seagrass association from the Maastrichtian of Kunrade and Nekami Quarry in the Netherlands. At these sites short lengths of silicified stem fragments and of root - stocks or holdfasts of the seagrass Thalassocharis are found together with an associated fauna of about 50 bryozoan species. Of these only a few were found exclusively on Thalassocharis the remainder being known to encrust other substrates.

Since this association probably evolved during the Upper Campanian and Lower Maastrichtian the author made an examination of specimens in his collection from those horizons to see if there was any evidence of bryozoans having grown around phytal substrates.

Whittlesea

A small number of specimens were found in the author's collection from Beeston and Sidestrand which had grown around phytal substrates as evidenced by their possession of hollows or channels in or through their zoaria.

At Sidestrand, in contrast to the silicified remains described by Voigt, pyritised phytal stems and stem fragments are occasionally found. Some of these show encrusting bryozoans. Unfortunately the surface detail on these pyritised remains is too poorly preserved for an accurate assessment of their taxonomic status to be made, but they were probably algal. The basal walls of the encrusting bryozoans show no useful information; certainly they lack the impressions of zig-zag leaf scars or longitudinal striations caused by long cells in the plant stems noted by Voigt in his material.

The diameter and spacing of the phytal stems varies between the two sites. At Beeston the average diameter is 2 mm whereas at Sidestrand it is under 1 mm. Moreover the zoaria from Sidestrand often enclose more than one stem; none of those from Beeston do. Hence at Beeston we appear to have relatively thick stems while at Sidestrand there appear to have been small "thickets" of thin closely spaced stems. These differences may be due to differences in the age of the plant, or may reflect genuine taxonomic diversity. The thin stems must have been fairly rigid, both to support the weight of the zoaria and to allow multi-laminar zoaria encrusting several stems to grow. It is unlikely that such zoaria could have grown if the stems were constantly moving relative to each other, e.g. because they were in a strong current. The number of specimens and species found thus far is much less than that described by Voigt. This is because the sites available from which to collect are both smaller and less fossiliferous than those of Kunrade and Nekami Quarry. Hence it is not possible to be so confident that the association found is a close one between the species noted, rather than opportunism on the part of the bryozoans. However it is noteworthy that in a majority of the specimens of *Micropora multicrescens* Brydone the hollow formerly occupied by the phytal substrate does not pass all the way through the zoarium indicating that the bryozoan larvae settled on or near the tips of the plant stem, that is to say on what was presumably the youngest part. This type of larval settling behaviour is well known amongst the larvae of those modern bryozoans which habitually encrust phytal substrates. This observation reinforces the conclusion that the inferred association is a genuine one. Furthermore, of those species found with evidence of phytal attachments *Porina lapidosa* Brydone is not known by the author to occur attached to other substrates, and *Cellepora accumulata* v. Hag. only very rarely does. Some of the species included by Voigt in his list of associated species are also recorded by the author from Beeston and Sidestrand, but because the relevant specimens do not represent the encrusting base one cannot be certain that they were part of the inferred association. The species which are included in the asssociation by the author are listed below for each locality.

Beeston, North Norfolk. Campanian, zone of *Belemnitella mucronata*, Beston Chalk.

1. *Tricephalopora sherborni* (Brydone)
2. *Porina lapidosa* Brydone
3. *Exochella eleanorae* (Brydone)

Sidestrand, North Norfolk. Maastrichtian, zone of *Belemnella lanceolata*, *Porosphaera* Beds.

Whittlesea

1. *Micropora multicrescens* Brydone
2. *Coelopora* sp.
3. *Porina lapidosa* Brydone
4. *Cellepora accumulata* von Hagenow.

Acknowledgements

The author would like to thank Diana Smith and Sylvia Turner (both of the Norwich Castle Museum) for their kind assistance.

Reference

Voigt, E. 1981. Upper Cretaceous Bryozoan - Seagrass Asssociation in the Maastrichtian of the Netherlands. *In* Recent and Fossil Bryozoa. G.P. Larwood and C. Nielsen (Eds.).

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Foraminifera from the Coralline Crag of Suffolk

Doppert, J.W.Chr.*

(Editors' Note: This short account of foraminifers from the Coralline Crag, and the correlations they suggest with Dutch and Belgian deposits, is based on a letter addressed by the author to Philip Cambridge, who had provided him with the samples from which the foraminifers were extracted. The letter was dated 5 June 1980. We are most grateful to Dr. Doppert for giving us permission to publish his results in this form.)

Foraminifera were examined from 11 samples:

A. Borehole 2 (39' - 43'), Orford, TM 4333526

B. Borehole 6 (30' - 38'), near Orford, TM 446553

C. Ramsholt Cliff, River Deben, TM298428

D. Gomer (lower part of excavation), Gedgrave, TM399489

E. Bullockyard Pit, Sutton Knoll (base of hole 1977), TM 306440

F. Bullockyard Pit, Sutton Knoll (upper part of pit), TM 306440

G. Sudbourne Park Pit 2 (lower part of pit), TM 407514

H. Sudbourne Park Pit 1 (upper part of pit), TM 407514

I. Tattingstone 3 (basal), TM 143374

J. Tattingstone 2 (3 to 3.55m), TM 143373

K. Tattingstone 1 ("5CC4" pit), TM 143374

The approximate numbers of foraminifers per 100 gramme of sediment were: A (11,000), B (12,000), C (42,000), D (6,000), E (22,000), F (16,000), G (19,000), H (10,500), I (23,000), J (6,500), K (28,000).

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The occurrence of foraminifers is indicated in the following table (where 1 = 1%, 2 = 1-5%, 3 = 5-15%, 4 = 15-30%, 5 = 30-50%):

	SPECIES	LOCALITIES										
		A	B	C	D	E	F	G	H	I	J	K
1.	Alliatinella gedgravensis		1				1			1		
2.	Ammonia beccarii	2	2	1	1		1		1	1	1	1
3.	Amphicoryna scalaris			1								
4.	Aubignyna mariei			1	1	1		1	1	1	1	1
5.	Bolivina imporcata			1	1	1		1			1	1
6.	Bolivina spec. div.	1	1	1					1	1		1
7.	Brizalina catanensis			1	1	1		1		1	1	1
8.	Buccella frigida			1	1	2	1	1	2	1	2	2
9.	Bulimina aculeata			1				1				
10.	Bulimina spec. div.									1		
11.	Cassidulina carinata + carinate forms			1	1	1	1	1		2	1	2
12.	Cassidulina laevigata + non-carinate forms	3	3	3	2	3	2	3	1	2	2	2
13.	Cassidulinoides bradyi					1						
14.	Cancris auriculus			1	1	1		1				
15.	Cibicides spec. div.	5	4	4	4	4	5	4	5	5	5	5
16.	Cribrononion excavatum				1							
17.	Cribrononion haagensis	2	2	2	2	2	1	2	1	2	2	1
18.	Dentalina spec. div.				1				1			
19.	Discorbis mira	1		1		1	1				1	1
20.	Discorbitura cushmani	1		1	1	1		1	1	1	1	1
21.	Discorbitura sculpturata	1	1	1	1							
22.	Elphidium crispum		1	1	1	1	1			1	1	1
23.	Elphidum pseudolessonii									1		
24.	Elphidium spec. div.	1	2	2	2	1	2	2	2	2	1	2
25.	Epistominella oveyi	1	1	1		1	1			1		
26.	Eponides umbonatus			1	1	1		1				
27.	Faujasina subrotunda								1	1		1
28.	Fissurina formosa + var. comata	1			1	1	1			1	1	1
29.	Fissurina laevigata			1	1	1	1	1		1	1	1
30.	Fissurina orbignyana	2	1	1	1	1	1	1		1	1	1
31.	Fissurina orbignyana var. clathrata	1		1		1				1		
32.	Fissurina orbignyana var. lacunata		1	1	1	1	1	1		1	1	1
33.	Fissurina quadrata			1	1	1				1		1
34.	Fissurina spec. div.	2	1	1		1	1	1	2	1	1	1
35.	Florilus boueanus	3	2	3	1	2	1	2	1	1	1	1
36.	Frondicularia spec. div.			1	1		1			1	1	1
37.	Gavelinopsis lobatulus		2	1	1	2	1	2		1	1	1
38.	Glandulina laevigata			1	1			1				
39.	Globigerina spec. div.	2	2	2	3	2	2	1	2	2	2	3
40.	Globulina gibba	2		1	1	1	1	1	2	1	1	1
41.	Globulina gibba var. fissicostata				1	1		1				1

Coralline Crag Foraminifera

		A	B	C	D	E	F	G	H	I	J	K
42.	Globulina gibba var. punctata	1	1	1			1	1				
43.	Globulina paucicrassicosta	2	1	1	1	1	1	1	2	1	1	
44.	Guttulina lactea			1	1	1	1		1			1
45.	Guttulina problema			1	1	1	1		1	1		1
46.	Guttulina spec. div.			1							1	
47	Hanzawaia boueana		1	1	1	1	1	1	2	1	1	1
48	Heronallenia lingulata			1		1		1	1	1	1	1
49.	Heterolepa dutemplei									1	1	
50.	Lagena costairregularis	1		1	2	1		1				1
51.	Lagena striata			1		1						
52.	Lagena spec. div.	2		1	1	1	1	1	1		1	1
53.	Lenticulina spec. div.			1	1					1	1	
54.	Monspeliensina pseudotepida		1	1	1	2		1		1	1	1
55.	Melonis affine	1		1		1	1		1	1		1
56.	Neoconorbina milletti		1	1	1	1		1		1	1	1
57.	Neoconorbina terquemi		2	1	1	1				1	1	1
58.	Nonion crassesuturatum	1	1	1	1	1		1	1	1	1	2
59.	Nonion granosum	2	1	1	1	2	2	1		1	1	1
60.	Nonion spec. div.	2	1		1	1	1	1	1			
61.	Nodosaria spec. div.								1	1		
62.	Oolina acuticosta			1			1	1		1	1	1
63.	Oolina hexagona		1	1	1	1		1			1	1
64.	Oolina melo			1	1	1	1	1		1	1	1
65.	Oolina seminuda	2	1	1	1	1	1	1	1			
66.	Oolina spec. div.			1	1		1		2		1	1
67.	Pararotalia serrata		2						1		1	
68.	Planorbulina mediterranensis	1	1	1	1	2	2	1	1	1		2
69.	Planularia pannekoeki			1						1		
70.	Polymorphina charlottensis				1				1		1	1
71.	Pseudopolymorphina jonesi			1								
72.	Pseudopolymorphina ovalis			1	1		1	1				
73.	Pseudopolymorphina spec. div.	1	1	1	1	1	1	1	1	1	1	1
74.	Pseudopolymorphina subcylindrica							1				1
75.	Pullenia bulloides			1	1	1		1				
76.	Pullenia quinqueloba			1								
77.	Quinqueloculina spec. div.		2	2	1	1	1	2	1	1	1	1
78.	Reussella spinulosa		2	1								
79.	Rosalina globularis	1	2	1	2	2	2	2	1	1	1	1
80.	Rosalina williamsoni		1	1		1		1	1	1	1	1
81.	Sagrina subspinescens			1	1			1				
82.	Siphotextularia spec. div.		1		1	1		1	1			1
83.	Spiroloculina depressa		1		1		1	1				
84.	Textularia decrescens	2			2	1	2	2	2		1	
85.	Textularia pseudotrochus	2	1	1	2	1	1	2	2	1	1	1
86.	Textularia sagittula (Spiroplect. deperdita)	3	2	2	2	3	2	2	2	1	2	2
87.	Textularia spec. div.	2	2	1	1	1	2		2			2
88.	Textularia truncata	1		1	1	1	1	1	3	1	1	2
89.	Trifarina angulosa	1	3	1	1	1	1	2	1	2	2	2
90.	Trifarina bradyi	2	2	2	1	2	1	2	1	3	3	3

Doppert

In order to make a biostratigraphical correlation between the Coralline Crag of Suffolk and the foraminiferal zones established in the Netherlands and Belgium it is not necessary to identify all the foraminifers to species level. Therefore various species are grouped together in the above Table under their generic name with the addition *spec. div*.

The foraminifers of the Coralline Crag samples examined comprise assemblages similar to those which characterise the FB-Zone of the Netherlands and the BFN5-Zone of Belgium. Of particular significance in these assemblages are the high values of species of *Cibicides* and *Textularia* (including *T. decrescens*), and the absence of *Elphidiella hannai* (a species which characterises younger, i.e. Upper Pliocene and Lower Pleistocene zones).

Samples C, D, E and G contain foraminifers which may indicate equivalence with the earlier, basal part of the Netherlands' FB-Zone. In general, in the lower part of the FB-Zone there are lower percentages of *Cibicides* spec. div. and higher percentages of *Cassidulina laevigata* compared with the upper part of that zone. *Cancris auriculus, Bolivina imporcata, Eponides umbonatus, Florilus boueanus, Lagena costairregularis, Monspeliensina pseudotepida, Pseudopolymorphina subcylindrica* and *Sagrina subspinescens* also occur in the same 3 samples. These species, although they may occur in the lower part of the FB-Zone, are more consistently present, or occur in distinctly high percentages in the even older FC-Zone of the Netherlands' succession.

In Belgium it is the Luchtbal Sands which contain the BFN5-Zone foraminifers, the equivalent of the Netherlands' FB-Zone.

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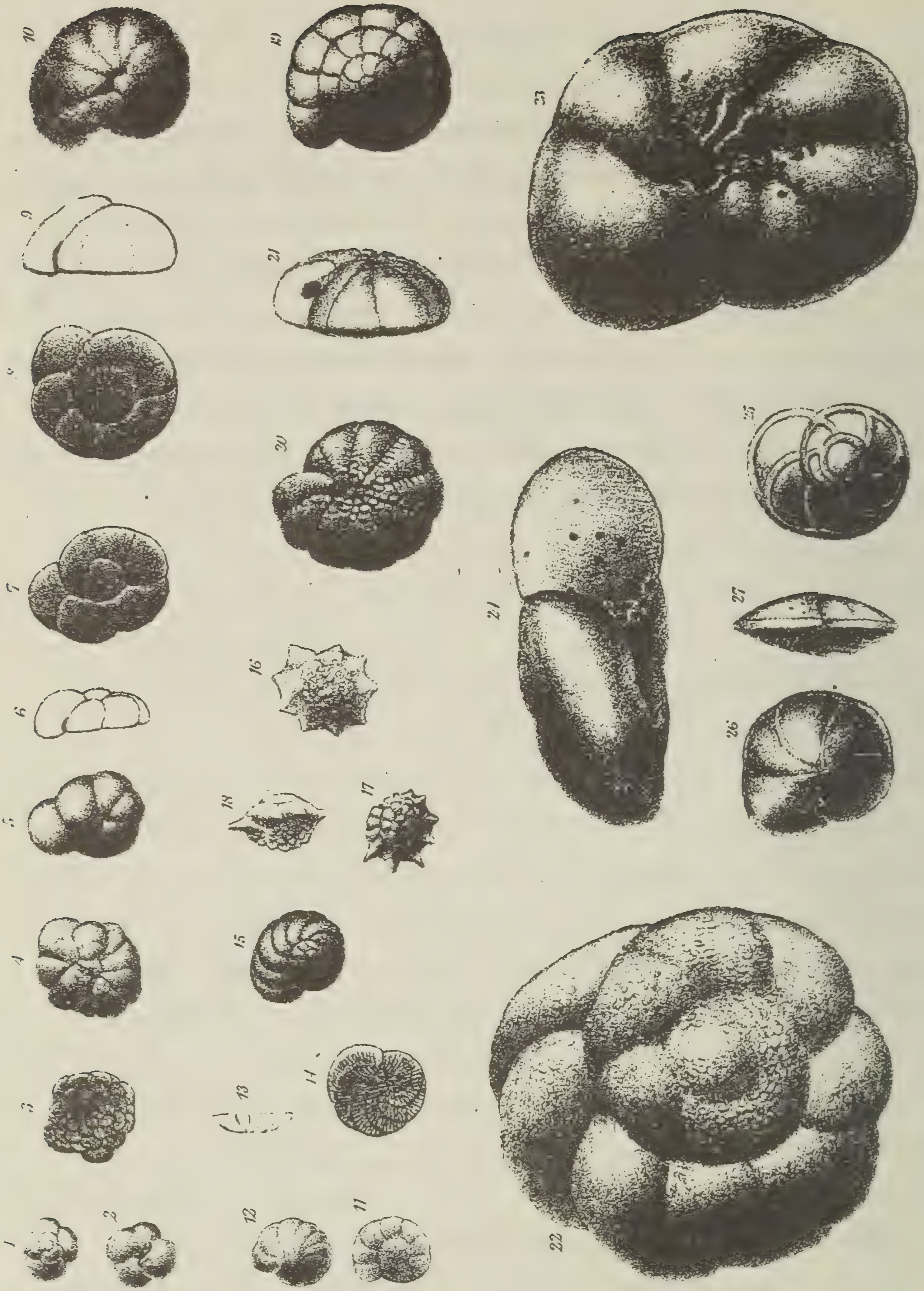
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CORALLINE CRAG FORAMINIFERS

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The Pleistocene Birds of South-Eastern England

C.J.O. Harrison*

Abstract

Pleistocene bird remains occur in a number of deposits from north Norfolk to north Kent, covering periods from the Early Pleistocene (Red Crag) to the Late Devensian. In general material is scanty. Although the list is obviously incomplete, 53 species are identified; half of them are water-birds, another five waterside-birds. There are five extinct species, four of them only known from this region, and including the only two birds known from the Red Crag. There is no significant body size variation, except in the Eagle Owl (_Bubo bubo_) in which a Pastonian individual is small, and a Hoxnian one as large as present-day forms. The species are tabulated, and wherever possible the standard (Mitchell _et al_. 1973) glacial and interglacial stage divisions indicated. The Cromer Forest Bed Series fauna is rich in waterfowl and contains a small passerine forest fauna; the land-birds of Ightham Fissure at the end of the Devensian may allow some inferences about climate at the time.

Introduction

The data in this paper (Table 1) were originally assembled for a talk on Pleistocene birds given at a meeting of the Geological Curators' Group at Norwich Castle Museum in September 1984, during an exhibition on the Ice Age in East Anglia.

The Ice-Age fauna reviewed here is that of south-eastern and eastern Britain as identified from several sites from north Norfolk to

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the Thames Valley and north Kent. I find that in conjunction with my colleague C.A. Walker we appear to have examined, and in some instances re-identified, all the material involved, and as a result have accumulated information on the presence of birds from Early Pleistocene Red Crag to the end of the Devensian Glaciation.

The British Pleistocene bird faunas can conveniently be divided into two. To the north and west there are remains found in caves, and to the south and east those found mainly in waterborne deposits. Both are samples of the avifauna, however inadequate, but they differ in their bias. With the exception of a few regular cave-haunters, western and northern birds are those which were carried into caves by predators, or the remains of the predators themselves. The south-eastern birds are those which came to grief in other ways, and whose bones were buried in mud or sand before they could be destroyed by scavengers. One very apparent bias resulting from this is the large proportion of gamebird bones in caves, and the predominance of water-birds in the other remains.

53 birds have been identified in Pleistocene deposits of the south-east. Five are extinct species. Of the remainder half are water-birds, another tenth waterside-birds, and of the 20 land-birds four are predators. Compared with relative percentages of our present-day avifauna, the earlier fauna shows an expectedly high number of water-birds, 50% as opposed to 21%. Surprisingly there are a smaller number of water-side birds, 10% instead of 25%, and a slightly smaller proportion of land-birds and raptors, 32% instead of 44% and 8% instead of 10%.

The Pleistocene list is obviously incomplete. During some periods tundra species such as the Snowy Owl (Nyctea scandiaca) must have been periodically present in large numbers in this region, but do not occur in the remains.

During the Pleistocene as a whole this avifauna does not differ markedly from that of north-west Europe at the present. In addition the bones of most species other than the Eagle Owl (Bubo bubo) do not show significant size differences from those existing at present. This probably reflects the mobility of most bird species which tend to respond to climatic change by rapid movement, leaving when conditions deteriorate and moving back when they improve, with little need for special adaptation.

This general mobility reduces the usefulness of birds as climatic indicators, particularly those in the deposits we are now considering. When Ptarmigan occur in the caves of Somerset and Devon, it may be inferred from the knowledge that they do not move far annually that conditions were colder than at present. However, in the south-east the presence of ducks and geese, or of a species such as the Wheatear (Oenanthe oenanthe) which may migrate north to the Arctic tundras and south to Africa south of the Sahara, do not give any real indication of the weather at the time. The number of useful climatic indicator bird species is limited, but the combination of species present in a locality may be an indication of some of the conditions of habitat and hence of climate.

The material available for this study is bird bones, usually individual and separate, and sometime incomplete. They are identified by comparison with recent osteological specimens. There has been a tendency to assume, where birds are concerned, that it is possible to extrapolate from what is present in a region today to what should have been present during glacial or interglacial periods, and some lists published in the past have been influenced by this. My personal view is that if identification is to be by direct comparison with recent specimens, then it must be done as objectively as possible throughout, and there should not be any preconception concerning a past fauna. This may result in some slightly unexpected species, but they should not be omitted because they appear unlikely, or assigned to the nearest similar species, as seems sometimes to have occurred.

In studying this succession of south-east England Pleistocene birds the standard glacial and interglacial stage divisions (Mitchell et al. 1973) have been used. I am aware that there are a far greater number of alternating climatic fluctuations than was originally believed and that it is no longer possible to glibly assign a stratum to a precise phase without a careful dating technique. However, we are concerned here with a group of vertebrates in which Ice-Age changes are very slow or virtually non-existent, and a combination of locality and the broader divisions of the Pleistocene make it possible to discuss the overall picture and to avoid the issue of precise limits between strata and climatic stages.

Early Pleistocene

The earliest evidence of eastern Ice-Age birds is in the Early Pleistocene Red Crag of Suffolk, and seems to show evidence of the last of the Pliocene fauna, both species now being extinct.

The Pleistocene period ushered in a deterioration of climatic conditions, with great extremes. One group obviously affected was the sea-birds. The huge Bony-toothed Seabirds , Odontopterygiformes, which may have dominated the seas for about fifty million years or more, at least from the Palaeocene onwards, and which had become adapted as giant marine gliders, disappear at the end of the Pliocene

(Harrison and Walker, 1976). The other large gliders, the albatrosses, Diomedeidae, also seem to have been affected.

In some earlier period, Pliocene or possibly earlier, an albatross appears to have penetrated into the northern hemisphere seas and produced two isolated but related species. The North Pacific one, the Short-tailed Albatross (Diomedea albatrus) has survived until the present, although ironically threatened with extinction by a combination of Japanese plumage hunting and the fact that it nests on actively volcanic islands. The North Atlantic Albatross (D. anglica) was present in the Atlantic, known from both Florida and Britain in the Early and Late Pliocene. It persisted into the Early Pleistocene in the Red Crag of England, and is not known subsequently (Harrison and Walker, 1978a).

The other Red Crag bird is Storer's Black Guillemot (Cepphus storeri) (Harrison, 1977). There are three extant species with a distribution suggesting Ice-Age speciation. The Black Guillemot (C. grylle) extended from the Atlantic to colonise the Arctic Ocean; the Pigeon Guillemot (C. columba) is in the north Pacific; and the Sooty Guillemot (C. carbo) is in the Sea of Okhotsk. The Early Pleistocene bird has some similarity to the last but is either another isolate, or more probably ancestral to all of these.

These seem to have been part of a disappearing avifauna, but the only specimen from the Norwich Crag, from near Southwold in Suffolk, which was identified as a Guillemot by E.T. Newton (1891) is in fact a Longtailed Duck (Clangula hyemalis) seemingly no different from our present-day winter visitors (Harrison, 1978a).

The Cromer Forest Bed Series

The largest source of Pleistocene bird material from this region is in the Forest Bed Series of north Norfolk (Harrison, 1979a). Most specimens are from the temperate period within this series. From the earliest, the Pastonian, there are Bewick Swan (*Cygnus bewickii*), Mallard (*Anas platyrhynchos*), a Buzzard, either Common Buzzard (*Buteo buteo*) or Rough-legged (*B. lagopus*), Guillemot (*Uria aalge*) and Razorbill (*Alca torda*). If the Bewick Swan were a winter visitor these could occur around the Norfolk coast today.

The other species present in the Pastonian is the Eagle Owl. It was obviously a major predator in the Pleistocene. It shares with the Starling (*Sturnus vulgaris*) the distinction of being the only landbird to occur twice in the deposits under consideration! In addition to its Forest Beds occurrence it also occurs at a later period in the Hoxnian of Swanscombe in north Kent. It occurs additionally in a number of northern and western caves and appears to have been fairly common. It is sometimes suggested that it may have persisted in Britain after the Pleistocene, and one wonders when and why we lost it. Climate does not seem to be the answer, in view of its distribution elsewhere. Man's activities would seem a more likely reason. It is possible that its choice of nest-sites was too close to the kinds of places in which man had an interest, but if it was killed off by early settlement it is surprising that so striking a bird left no legend or folk-memory.

It is also of interest that the earlier specimen, from the Forest Bed, is small. The present-day Eurasian Eagle Owl is large, possibly the largest owl. In the desert region of North Africa and the Middle East there is a much smaller form with pale plumage, very distinct in size, although at present treated as a race of the norther species, the two have obviously diverged during some period of isolation. The

Forest Bed bird is as small as this desert form. I am tempted to suspect that the ancestral Eurasian Eagle Owl may have been a smaller bird, and it is possible that the large northern one that we know today may have evolved during the later Pleistocene, possibly because it was one of a few species, with a wide spectrum of prey, that might have had a greater interest in remaining where it was and adapting to colder conditions.

The Cromerian provides more abundant material. Stuart (1975) has reconstructed a background for the Upper Freshwater Beds, in which this material originates, of a temperate mixed oak forest with some fen and herbaceous vegetation. There must have been extensive open water, since it provides the country's richest array of Ice-Age water-birds. The Cormorant (Phalacrocorax carbo), is present, and Bewick Swan occurs again, with Greylag Goose (Anser anser). Among dabbling ducks there are Mallard, Wigeon (Anas penelope) and Teal (A. crecca). There are diving ducks - Redcrested Pochard (Netta rufina), Tufted Duck (Aythya fuligula), Pochard (A. ferina) and Goldeneye (Bucephala clangula) - and two saw-billed fish-eaters - the Smew (Mergus albellus) and Redbreasted Merganser (Mergus serrator). Most of these might occur today, but the Redcrested Pochard is a more southerly and easterly Eurasian species at present, and its occurrence may indicate warmer and drier conditions.

There is also an extinct species (Harrison, 1979a), the Thick-legged Eider (Somateria gravipes), differing in this respect from extant eider species to the same extent that they differ from each other. Mlikovsky (1982) has claimed to show statistically that this is a form of the Common Eider, but the arguments are not wholly convincing.

The Moorhen (*Gallinula chloropus*) and Green Sandpiper (*Tringa ochropus*) are likely to have occurred on the margins of fresh water. There is a passerine population including Blackbird (*Turdus merula*), Song Thrush (*T. philomelos*) or Redwing (*T. iliacus*), Nuthatch (*Sitta europaea*), Starling (*Sturnus vulgaris*) and Jay (*Garrulus glandarius*) that would not be out of place in a present-day mixed oak-wood. The Jay in particular is now closely linked in its present distribution with that of oaks.

A species of special interest is the Mandarin Duck (*Aix galericulata*). It may seem at first slightly improbable, and further confirmatory material would be helpful. Its present range is further east than that of the Redcrested Pochard, in eastern China. Interestingly it is a bird of oak forest in that region, and in southern England introduced birds have become feral in such habitats, where it is a bird of woodland ponds and streams. It is really no more unlikely in terms of distribution than the Azure-winged Magpie (*Cyanopica cyanea*) which, were it not for its limited range in Spain and Portugal, we would assume to have evolved in isolation in southern China where it also occurs (Harrison, 1982). The identification does emphasise the fact that it cannot be assumed that one need only compare specimens with those found in Europe today.

A small fauna from Ostend, Norfolk, appears to have originated in temperate conditions and includes with Pochard and Common Scoter (*Melanitta nigra*) the Redcrested Pochard. The fourth species from this locality (Harrison, 1978b) is another interesting bird, the extinct European Jungle fowl (*Gallus europaeus*) (Harrison, 1978b). When Pleistocene bird bones from the London Basin were examined (Harrison and Walker, 1978b) a *Gallus* fowl bone from the Ipswichian of

Crayford presented a problem. All that could be done at the time was to list four alternative interpretations. With the discovery of another bone in the Cromerian material it was evident that a form of Gallus was present in the English Pleistocene, not obviously linked with the Red Jungle fowl (Gallus gallus) of India from which all our domestic birds are allegedly derived.

In the gamebirds the post-Pleistocene distribution pattern often shows three species (Harrison, 1982); one in the Western Palaearctic, in Europe and perhaps extending as far east as the Tibetan-Altai cold barrier; another in the Eastern Palaearctic; and sometimes a third in the Indian Region south of the Himalayas. The Quails (Coturnix species), and common Partridges (Perdix species), both show this pattern, and it seems that the junglefowl may have had a similar distribution and that this is the Western Palaearctic form.

The only species associated with a cooling period at the end of the Forest Bed Series are a Redthroated Diver (Gavia stellata) and Common Scoter from Mundesley.

Swanscombe

The next youngest deposits with birds in the English Pleistocene succession are at Swanscombe in north Kent (Harrison, 1979). A small fauna has been assigned to the Hoxnian Interglacial and includes some inevitable ducks - Shoveler (Anas clypeata) and Redbreasted Merganser. It has an Eagle Owl which is as large as the present European form, and two small passerines, Garden Warbler (Sylvia borin) and Serin (Serinus serinus). The last was, until recently, a mainly Mediterranean species, and its presence suggests that the climate in summer at least might have been warmer and drier than at present. It should perhaps be pointed out that since many birds are migratory their presence may give information about one season of the year but indicate nothing about the other extreme. This is illustrated in more striking form in late Pleistocene material from Tornewton Cave in South Devon (Harrison, 1980b) where White Storks (*Ciconia ciconia*), possibly breeding birds, occur in what is thought to be a cool period.

Some of the Swanscombe birds have been assigned to the subsequent Wolstonian Glacial period. They are nominal Boreal species, including Whitefronted Goose (*Anser albifrons*) and Barnacle Goose (*Branta leucopsis*), which now breed in the Arctic, and a big grouse, the Capercaillie (*Tetrao urogallus*). The latter is a forest or forest-edge species, usually associated with boreal-type conifer forest, but there may be reservations about this. Yapp (1983) found evidence of Capercaillie in England, possibly in East Anglia, in Medieval times, and since there is an isolated population in the mountains of north-west Spain that in winter relies on holly and not conifer, it is possible that the species is more adaptable that has sometimes been supposed.

We have lost one grouse species. Although it has not so far been found in these south-eastern sites, material from elsewhere indicates that through most of the Pleistocene, including the end of the last glaciation, when forest was present the Hazelhen (*Tetrastes bonasia*) was found here. This is a small grouse inhabiting forest of more open kind with shrubby undergrowth, and still occurring in much of Europe. It seems likely that it disappeared through human agency. From its present-day distribution it looks as though it prefers a continental climate where cold winters are counterbalanced by warmer, drier summers, and possibly our milder, moister Atlantic-type climate was unsuitable for its survival.

London Basin

Scattered specimens from various localities in the London Basin have been assigned to the last, Ipswichian interglacial (Harrison and Walker, 1978b). Water-birds again predominate. There is a Cormorant, a Whooper (Cygnus cygnus) or Mute Swan (C. olor), Greylag Goose, Whitefronted Goose, Mallard, Gadwall (Anas strepera), and Smew, all species that might occur today. An exception is the Redbreasted Goose. This now breeds in a limited area of Siberian tundra and winters on the plains of eastern Europe, occasional individuals straying this far west.

The land-birds include the European Junglefowl, already mentioned, and the Coot (Fulica atra). An extinct species that occurs here as the earliest record (Harrison and Cowles, 1977) is the European Crane (Grus primigenia, Milne-Edwards, 1896). This is another instance of a distribution pattern similar to that of the junglefowl. In most parts of the northern hemisphere there are usually two crane species, one larger and one smaller. In North America there is the Whooping Crane (Grus americana) and Sandhill Crane (G. canadensis). Through the Palaearctic the smaller species is the Common Crane (Grus grus). In the Eastern Palaearctic there is a large Manchurian or Japanese Crane (G. japonensis); and in India where the smaller species winters but does not breed, the large Sarus Crane (G. antigone).

There is now evidence of this large crane, apparently adapted to cool climates, in north-west Europe, where it filled a gap now vacant in the Western Palaearctic. It was also present in the Devensian Glaciation, is known from west Germany and northern France, occurred in the Bronze Age in Scotland, at the Iron Age lake settlement at

Glastonbury, and is last known from a fragment in a Romano-British midden. In the areas of the northern hemisphere where two species breed the smaller form is mainly grey, the larger mainly white, and it seems likely that the European Crane had a white plumage.

During the last glacial period, the Devensian, the London Basin had Greylag Goose, Mallard, Tufted Duck and White-tailed Sea-Eagle (*Haliaeetus albicilla*). Although the last is the only occurrence of this eagle in the south-east in the Pleistocene, it not infrequently occurs elsewhere and was the typical lowland eagle. All eagle specimens from the southern half of Britain that have been re-examined have proved to belong to this species. Some had been erroneously attributed to the Golden Eagle but this was a more restricted mountain species.

Ightham Fissure

The final fauna listed here is from Ightham Fissure in Kent (Harrison, 1980a). This is a cave-type site that appears to date from the end of the last glaciation, although there are some more recent anomalies, such as domestic-type duck remains, possibly introduced into earlier strata by a fox.

It has Whitefronted Goose, Mallard, Wigeon, Shelduck (*Tadorna tadorna*) and Common Scoter. This is an inland site and the last two are estuary or coastal species, but since this is a predators' site they may have come from the proto-Medway and this suggests that White-tailed Sea-Eagle might be involved, as at Tornewton Cave (Harrison, 1980b).

Shorelark (*Eremophila alpestris*) and Snow Bunting (*Plectrophenax nivalis*) hint at colder conditions, or may have been winter visitors. Swallow (*Hirundo rustica*), Skylark (*Alauda arvensis*), Yellow Wagtail

(Motacilla flava), Wheatear and Starling suggest the presence of open grassland and in aggregate are birds of more temperate conditions. Three species, a small eagle that might have been Bonelli's Eagle (Hieraaetus fasciatus) or Booted Eagle (H. pennatus), the Spotted Crake (Porzana porzana) and Crested Lark (Galerida cristata), are now European mainland species that might argue for warmer conditions than at present, although the last comes as close to Britain as the north coast of France and the Spotted Crake occasionally nests in Britain. However, all tend to come further north in eastern Europe, and they may indicate that towards the end of the Pleistocene the climate was more continental in type, with hotter, drier summers accompanying the cold winters. This would be in accordance with the presence at that time of other vertebrates such as the European Pond Tortoise (Emys obicularis) (Stuart, pers. comm.) which finds out present summers too cool or uncertain to allow its eggs to hatch.

In spite of the sparse and scattered material, it provides in summary a framework into which further information on the avifauna of the region can be fitted to create an increasingly useful picture of Pleistocene birdlife, and although it is limited some inferences can already be drawn from it concerning habitats and climate, and tested against those available from studies of other groups of animals and plants.

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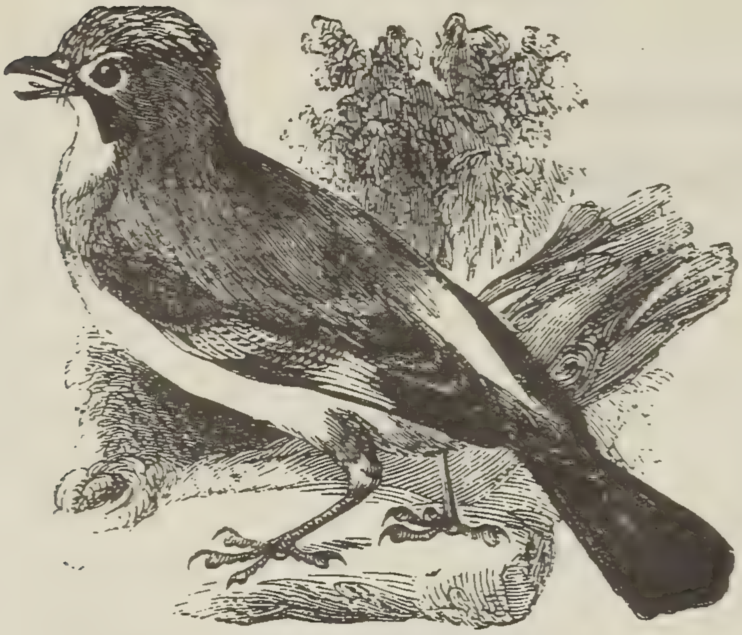
Table 1: Pleistocene Birds Of S.E. England	RED CRAG	ICENIAN CRAG	FOREST BED SERIES				SWANSCOMBE		LONDON BASIN		IGHTHAM FISSURE
		Norwich Crag	Pastonian	Cromerian	Ostend	Mundesley	Hoxnian	Wolstonian	Ipswichian	Upper Devensian	Upper Devensian Holocene
North Atlantic Albatross *Diomedea anglica*	*										
Red-throated Diver *Gavia stellata*						*					
Cormorant *Phalacrocorax carbo*				*					*		
Whooper Swan *Cygnus cygnus* Mute Swan *Cygnus olor*									*		
Bewick's Swan *Cygnus bewicki*			*	*							
Greylag Goose *Anser anser*				*					*	*	
Whitefronted Goose *Anser albifrons*								*	*		*
Barnacle Goose *Branta leucopsis*								*			
Redbreasted Goose *Branta ruficollis*									*		
Shelduck *Tadorna tadorna*											*
Mandarin Duck *Aix galericulata*				*							
Mallard *Anas platyrhynchos*			*	*					*	*	*
Gadwall *Anas strepera*									*		
Wigeon *Anas penelope*				*							*
Teal *Anas crecca*				*							
Shoveler *Anas clypeata*							*				
Redcrested Pochard *Netta rufina*				*	*						
Tufted Duck *Aythya fuligula*				*						*	
Pochard *Aythya ferina*				*	*						
Thicklegged Eider *Somateria gravipes*				*							
Longtailed Duck *Clangula hyemalis*		*									
Common Scoter *Melanitta nigra*					*	*	├─	*─┤			*
Goldeneye *Bucephala clangula*				*							
Smew *Mergus albellus*				*					*		
Redbreasted Merganser *Mergus serrator*				*			*				
Whitetailed Sea Eagle *Haliaaetus albicilla*										*	
Common Buzzard *Buteo buteo* Roughlegged Buzzard *Buteo lagopus*			*								

Table 1 (continued): Pleistocene Birds of S.E. England

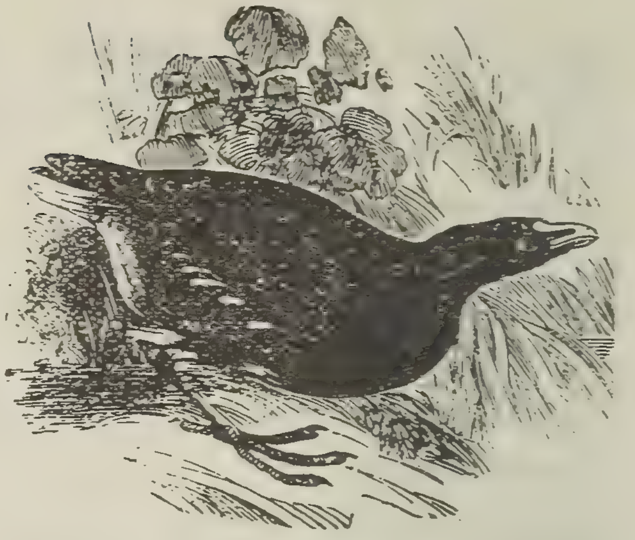
	RED CRAG	ICENIAN CRAG Norwich Crag	FOREST BED SERIES Pastonian	Cromerian	Ostend Mundesley	SWANSCOMBE Hoxnian	Wolstonian	LONDON BASIN Ipswichian	Upper Devensian	IGHTHAM FISSURE Upper Devensian Holocene
Booted Eagle *Hieraeetus pennatus* Bonelli's Eagle *Hieraeetus fasciatus*										*
Capercaillie *Tetrao urogallus*							*			
European Junglefowl *Gallus europaeus*					*			*		
European Crane *Grus primigenia*								*		
Moorhen *Gallinula chloropus*				*						
Coot *Fulica atra*								*		
Spotted Crake *Porzana porzana*										*
Green Sandpiper *Tringa ochropus*				*						
Storer's Black Guillemot *Cepphus storeri*	*									
Guillemot *Uria aalge*			*							
Razorbill *Alca torda*			*							
Eagle Owl *Bubo bubo*			*			*				
Swallow *Hirundo rustica*										*
Crested Lark *Galerida cristata*										*
Skylark *Alauda arvensis*										*
Shorelark *Eremophila alpestris*										*
Yellow Wagtail *Motacilla flava*										*
Garden Warbler *Sylvia borin*						*				
Redwing *Turdus iliacus* Song Thrush *Turdus philomelos*				*						
Blackbird *Turdus merula*				*						
Wheatear *Oenanthe oenanthe*										*
Nuthatch *Sitta europaea*				*						
Serin *Serinus serinus*						*				
Snow Bunting *Plectrophenax nivalis*										*
Starling *Sturnus vulgaris*				*						*
Jay *Garrulus glandarius*				*						

GARRŬLUS.—(Lat. *talkative.*)



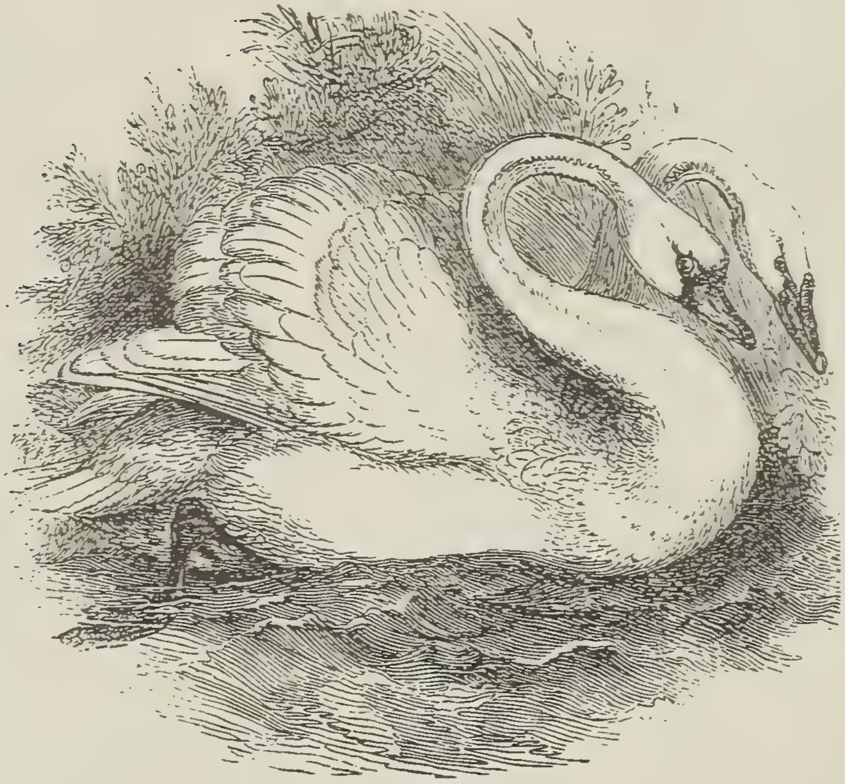
Glandarĭus (Lat. *of the Acorn*), *the Jay.*

GALLINŬLA.—(Lat.)



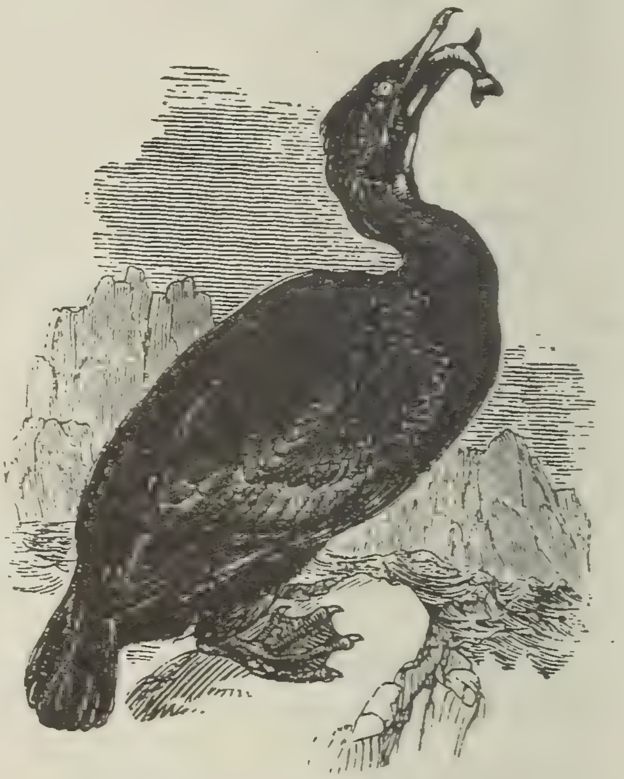
Chlorŏpus (Gr. Χλωρός, green, πούς, a foot) *the Water-hen.*

CYGNUS.—(Lat. *a Swan.*)



Olor (Lat. *a Swan*), *the Mute Swan*

PHALACROCŎRAX.—(Gr. Φαλακρός, bald; κόραξ, a Raven.)



Carbo (Lat. *a Coal*), *the Cormorant.*

PLEISTOCENE BIRDS

Bull. geol. Soc. Norfolk, 35, 71-72 June 1985

Catton Sponge Bed S.S.S.I. preserved for posterity

N.B. Peake*

After 12 years of discussion, punctuated by changes of ownership and plan, this key part of the former Catton Grove Pit now seems safe for future researchers.

Two huge pits at New Catton formerly exposed the upper half of the Weybourne Chalk horizon of the B. mucronata Zone, overlain by the 0.5 metre thick Sponge Bed, with up to 1 metre of Beeston Chalk above, capped by (unfossiliferous) Norwich Crag. The soft Weyborne Chalk was burned there for lime, whilst blocks of the hard Sponge Bed were left, unwanted, to weather on the pit floors. From these blocks came much of the "Norwich Chalk" material in our national collections, including many type specimens. Reportedly, the belemnites which abounded in the softer chalk were called "whistlefish" by the quarrymen - no doubt once their alveolar cavities were washed clean, they would serve as crude whistles!

A thinner, less well-defined sponge bed lay about 1 metre below the main one, and a third impersistent one almost 1 metre above. All three can, occasionally, be seen on the foreshore below Sheringham Lifeboathouse, and, in 1974, were also recognised in a temporary exposure at Stoke Holy Cross, 5 miles south of Norwich. Their regional significance is thus beyond doubt, and they probably equate with the "Nouvelles/Spiennes Gap" in Belgium, and with depositional breaks recognised in Co. Antrim and Germany. With minimal sedimentation, only hard-bottom-loving organisms (especially brachiopods and sponges) flourished, the latter including many undescribed genera of lithistids, as well as hexactinellids; external moulds of aragonitic forms, such as gastropods, are also common.

Quarrying from the northern ("Attoe's") pit ceased in the 1950's, although Jack Stevens, a transport contractor, continued to burn chalk there for lime. The chalk itself was excavated from deep-level sewer construction in Norwich. Long since infilled, it is now built over. The southern ("Campling's") pit was reaching its territorial limits at the same time, and an attempt was made to deepen it by smashing through the thick "tabular" flint band ("S" of the coast-section; Peake and Hancock 1961, 1970) which formed its floor. Breakthrough released a fountain of water under artesian pressure, which rapidly flooded the pit, and working was resumed only after extensive back-filling, which buried its limekiln. Thereafter 20-30 tons of chalk per week were taken to the kiln in an abandoned pit off Sprowston Road - the kiln remaining in work (the last to do so in east Norfolk) until 1963. This ("Mousehold") pit had been won, in 1912 in a game of poker from Mr. Edwards, by Robert Campling - a well-known sportsman and gambler! St. Georges Church now stands on its site. The Kiln remains as a "listed building", though sadly, unvisitable as the result of a bureaucratic faux pas which permitted Barratt Housing Ltd to block off one entrance, which had been necessary for safe ventilation.

---

* Scientific Anglian, 30 St. Benedicts's Street, NORWICH

The working kiln, and the Catton Grove Pit were shown to the British Association in 1961, Norwich Fire Brigade have obligingly cleaned the old faces with high-pressure hoses for the occasion! The pit itself has now been filled in by R.G. Carter Ltd who have generously constructed a semicircular "dam" of rubble-filled wire baskets ("gabions") to hold back the infill, and thus preserve a 12 metre long section of 2 to 3 metres of chalk which includes the main Sponge Bed, with overlying chalk and crag. This is being topped with a stout fence, including a locked gate; within the fenced area natural weathering will be allowed to talus-over the chalk, the talus eventually being turfed. The reason for this (unprecedented when first proposed) method of preserving the section is that it lies quite close to the site-boundary, and unrestricted collecting from it would cause so much "student erosion" that within a 20-year period, the entire Sponge Bed could be quarried entirely away. With the generous co-operation of the Museums Committee, it is being arranged that a key will be held at the Castle Museum, and those with a genuine research interest in the section will be permitted access, and will be able to cut away the turf to reveal the Sponge Bed when needed. No doubt, parties from the Geological Society of Norfolk will be able to visit the section from time to time, in a voluntary "management" capacity, to remove young trees, rubbish, etc.

This S.S.S.I. ("Site of Special Scientific Interest") will thus become a pleasant verdant feature in an otherwise built-up area. Grateful thanks are due to R.G. Carter Ltd for the co-operation they have shown, to the Nature Conservancy for its patient persistence, and to numerous individuals who have helped with clearance of the section from time to time. All these, and the Norfolk Museums Service, have helped to bring this project to such a satisfactory conclusion!

Reference

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CONTENTS Page

Editorial		1
Kelly, S.R.A.	Jurassic and Cretaceous deposits of Upware, Cambridgeshire	3
Whittlesea, P.S.	Notes on Chalk fossils: 1. A temporary section at Bramerton, 2. The brachiopod Kingenella kongieli in the Norwich Chalk, 3. Bryozoan - "Algal" association from the Upper Campanian-Maastrichtian	39
Doppert, J.W.Chr.	Foraminifera from the Coralline Crag of Suffolk	47
Harrison, C.J.O.	The Pleistocene birds of South-Eastern England	53
Peake, N.B.	Catton Sponge Bed S.S.S.I. preserved for posterity	71

The Geological Society of Norfolk exists to promote the study and knowledge of geology, particularly in East Anglia, and holds monthly meetings throughout the year.

Visitors are welcome to attend the meetings and may apply for membership of the Society. For further details write to the Secretary: Miss Diana Smith, Castle Museum, Norwich NR1 3JU.

Copies of the Bulletin may be obtained from the Secretary at the address given above; it is issued free to members.

The illustration on the front cover is taken from Figure 43 (page 514) of Lyell's "Principles of Geology", 1867 Edition, and shows the "Tower of the buried church of Eccles, Norfolk, A.D. 1839".

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BULLETIN OF THE GEOLOGICAL SOCIETY OF NORFOLK

(FOR ARTICLES ON THE GEOLOGY OF EAST ANGLIA)

No.36

1986

CONTENTS INCLUDE:

INDEX to Bulletin Nos. 1–35

Chalk potstone worms

Fenland Holocene mapping

Shingle Street lagoons

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INDEX VOLUME

BULLETIN of the GEOLOGICAL SOCIETY OF NORFOLK

No. 36

September 1986

Editor: Brian M. Funnell, School of Environmental Sciences,
University of East Anglia, Norwich NR4 7TJ

Assistant Editor: Philip G. Cambridge, 258 Bluebell Road, Norwich
NR4 7LW

EDITORIAL

The greater part of this issue is devoted to a comprehensive INDEX to the first 35 issues of this Bulletin. Numbers 1-15 were published in the years 1953-1967 as the "Paramoudra Club Bulletin", and Numbers 16-35 (after the Society changed its name) as the "Bulletin of the Geological Society of Norfolk" in the years 1968-85. The Index was initiated, as a card index under the guidance of our former Fieldwork Secretary, Peter Lawrence, with the help of young people engaged on the Youth Opportunities Programme. The card index was put into typed form by David Allen, but the major burden of checking, correcting and bringing it up-to-date was undertaken by Mrs. Pat Funnell, to whom the Society is very grateful. Mrs. Barbara Slade has also been a very great help in getting the final version "on disc". We trust readers will find it useful, and we hope they will not find too many errors or omissions remaining.

Because Nos. 1-18 were issued several years ago and in duplicated form only, we are planning a consolidated reprint in the current Bulletin format in the relatively near future. We expect them to make-up into two volumes in the present format.

After the Index I have inserted a speculative article of my own on the life-style of the marine worms which are associated with the origin of Chalk potstones. (Also called paramoudras, the potstones seemed a particularly suitable topic to accompany the Index of the Bulletin of a Society, which started life as the "Paramoudra Club"!)

Editorial

There follows a description of a new geophysical technique developed by the British Geological Survey for mapping Fenland deposits, and a report on a pilot study of the water characteristics of the lagoons of Shingle Street in Suffolk. The latter may seem a somewhat esoteric subject for a Geological Society, but in 1973 we published an article on the evolution of Shingle Street by Dr. Randall - see the Index!

We have some articles under consideration for publication in Bulletin No. 37 (due out in April 1987), but others would be welcome.

INSTRUCTIONS TO AUTHORS

Potential contributors should note that although we prefer manuscripts to be submitted in typewritten copy we will accept neatly handwritten material. It is most helpful if the style of the paper, in terms of capitalisation, underlining, punctuation, etc. is made to conform strictly to those normally used in the Bulletin. All measurements should be given in metric units. The reference list is the author's responsibility and should always be carefully checked.

Illustrations are important. They should be drawn with thin dense black ink lines. Thick lines, close stipple or patches of solid black should be avoided as these tend to spread in the printing process usually employed. Original illustrations should, before reproduction, be not more than 175 mm by 225 mm. Full use should be made of the first (horizontal) dimension, which corresponds to the width of print on the page, but the second (vertical) dimension is an upper limit only. Half-tone (photographic) plates can also be accepted, provided the originals exhibit adequate contrast, and when their use is warranted by the subject matter.

Editorial

Authors are reminded that the Bulletin of the Geological Society of Norfolk exists to publish research papers, notes or general articles relevant to the geology of *East Anglia* as a whole, and does not restrict consideration to articles covering the geology of Norfolk alone.

APOLOGIES and CORRIGENDA

We apologise that we did not acknowledge the source of the illustrations reproduced by us on pages 52 and 70 of Bulletin No. 35. The illustration of Coralline Crag Foraminifers on page 52 , is from part of Plate II, of the Palaeontographical Society's "A monograph of the Foraminifera of the Crag, Part 1", authors Jones, T.R., Parker, W.K. and Brady, H.B. and published in 1866. The illustrations of Pleistocene Birds on page 70, are from pages 176, 240, 243 and 253 of "The Boy's Own Natural History", published in the last century by Routledge.

Unfortunately we also find ourselves in the invidious position of having to issue a correction to a correction. The list of Corrigenda on page 2 of Bulletin No. 35 should refer to Bulletin No. 34, and not as printed.

Please note the following corrigenda to Bulletin No. 35.

Whittlesea

p.43, the title to Fig. 1 should read: *Kingenella kongieli* Popiel-Barczyk

Doppert

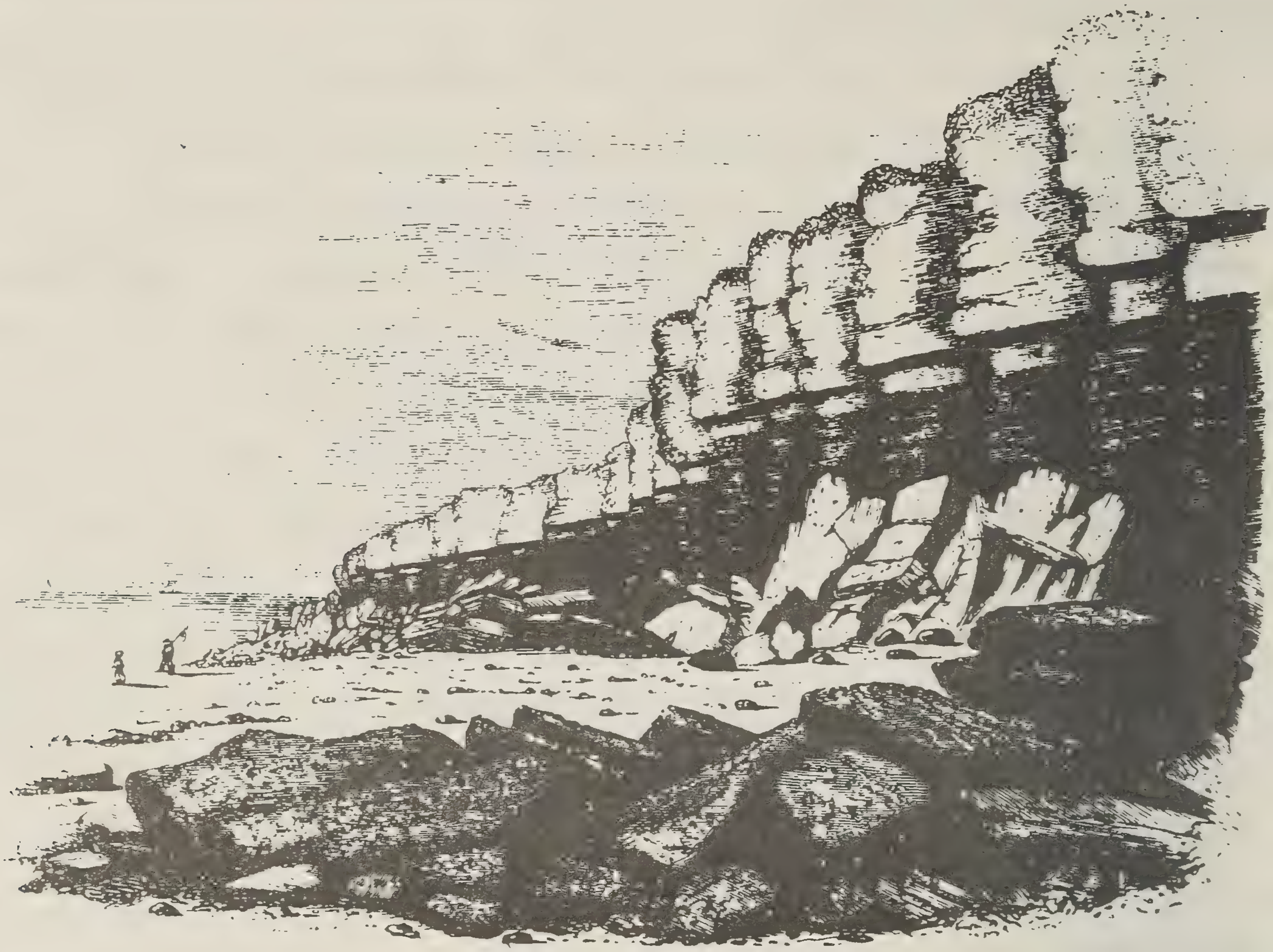
p.47, line 13; for 'TM 4333526' read 'TM 433526'
p.50, line 6 from bottom; for '3' read '4'

Harrison

p.65, line 15; for '*obicularis*' read *orbicularis*'

B.M. Funnell
P.G. Cambridge

BULLETIN OF THE GEOLOGICAL SOCIETY OF NORFOLK



No. 20

CONTENTS INCLUDE:

Origin of North Sea – Geology in Education – Zones of Gipping Valley Chalk – Forest Bed Horse jaw – Field meeting reports – Bibliography supplements.

(Reproduced as page 4 of Bull. geol. Soc. Norfolk, 36, Sept. 1986)

Bull. geol. Soc. Norfolk, 36, 5-76 September 1986

INDEX to the contents of Bulletin of the Geological Society of Norfolk (formerly the Paramoudra Club Bulletin) Nos. 1 to 35 (1953-1985)

compiled by Patricia A. Funnell and others.

SUMMARY OF CONTENTS, DATES OF ISSUE and EDITORS

Paramoudra Club Bulletin

No. 1 (September 1953) A.P. Baggs
  The Easton Bavents Cliff Sections, Southwold, Suffolk. G.P. Larwood and A.J. Martin
  Cliff Sections between Caister and Scratby. A.J. Martin
  Recent Work on the Constitution of the Chalk. G.P. Larwood

No. 2 (April 1954) A.P. Baggs
  An Abstract of Information obtained from Borings in Norwich, 1951. B.M. Funnell
  Notes on Some Exposures in Glacial Beds West of Norwich. B.M. Funnell

No. 3 (August 1955) G.P. Larwood
  A Survey of the River Tas Valley. B.R. Brown
  The Age of the Ostrea lunata Chalk at Mundesley, Norfolk, exposed 1898 and 1954. D.R. Howlett and G.P. Larwood

No. 4 (December 1955) G.P. Larwood
  A Study of the Cliff Section at Easton Bavents, near Southwold, Suffolk. D.E.H. Reeder
  Report on the Excursion to Runton. B.R. Brown

No. 5 (May 1956) G.P. Larwood
  The Evolution of the Southern North Sea Basin. B.M. Funnell
  The Glaciations and Interglaciations of East Anglia: a Summary and Discussion of Recent Research. R.G. West, summarised by A.J. Martin

No. 6 (February 1957) G.P. Larwood
  Field Meeting at Caistor St. Edmunds, Norwich. B.M. Funnell
  The Norwich Chalk Belemnitidae. B.M. Funnell

No. 7 (December 1957) G.P. Larwood
  The Differentiation and Correlation of East Anglian Pleistocene Deposits: a Review of Recent Research. B.M. Funnell
  The Cretaceous Setting of East Anglia. J.M. Hancock

No. 8 (March 1958) G.P. Larwood
  Hutton, Lyell and Smith in Norfolk. A.J. Martin

No. 9 (September 1959) G.P. Larwood
  Cretaceous Flint. S.V. Bell

No. 10 (March 1961) G.P. Larwood
  Patterned Ground: a Descriptive Review with emphasis on the Importance of Permafrost features in East Anglia. P.H. Banham

Bulletin (Nos. 1-35)

No. 11 (December 1962) G.P. Larwood
Glacial Tectonics: a Review and Discussion of the Application of Tectonic Concepts to the Structures Observable in Glacial Deposits. P.H. Banham

No. 12 (February 1965) G.P. Larwood
Glaciofluvial Deposits at Burgh Castle, Suffolk. J.A. Westgate
A Bibliography of Literature Describing Exposures of Beds Disturbed by Ice. C.E. Ranson

No. 13 (October 1965) G.P. Larwood
The Cromer Forest Bed Series. R.G. West
Quaternary Field Meeting at Birmingham. R.A.D. Markham
Surface of the Chalk in Norfolk. C.E. Ranson

No. 14 (January 1966) G.P. Larwood
Quaternary Field Meeting in Durham. C.E. Ranson

No. 15 (May 1967) G.P. Larwood
Reflections on the thicknesses of sedimentary formations. J.M. Hancock

Bulletin of the Geological Society of Norfolk

No. 16 (December 1968) G.P. Larwood
An assessment of the glacial deposits of North-East Norfolk. C.E. Ranson
Investigations into the geology of the site of the University of East Anglia. A.K. Fowler and M.R. Leeder

No. 17 (August 1969) C.E. Ranson
A preliminary account of research boreholes at Beccles and Gt. Yarmouth. A.R. Lord
Field Meeting to Bramerton, 20th April 1969. P.G. Cambridge
Field Meeting to Black Dyke Farm chalkpit, and to the shafts and tunnelworks for the Essex Water Abstraction Scheme, 8th June 1969. N.B. Peake and P.G. Cambridge
Bryozoa and the origin and development of the Cheilostomata. G.P. Larwood

No. 18 (November 1969) C.E. Ranson
Observations on iron mineral geodes in Norfolk. A.K. Fowler
Notes concerning some rhynchonellid and terebratulid brachiopods of the Upper Chalk zone of Belemnitella mucronata in Norfolk. M. Leeder
A preliminary account of two further research boreholes at Stradbroke and Hoxne, Suffolk. A.R. Lord
Interglacial beds at Beetley, Norfolk. R.A.D. Markham

No. 19 (April 1971) R.S. Joby
Soil surveying in Norfolk and Suffolk. W.B. Corbett
"Iron mineral geodes" of Suffolk. H.E.P. Spencer
Temporary exposure in the Drift near Cromer. P.H. Banham
Report of a field meeting in Breckland, 20 September 1970. C.E. Ranson

INDEX (1953-85)

No. 20 (September 1971) R.S. Joby
The Origin of the North Sea. B.M. Funnell
Aspects of Geology in Education. H. Evans
The Zones of the Gipping Valley Chalk, Suffolk. R.A.D. Markham
A Forest Bed Horse Jaw from Paston, Norfolk. R.A.D. Markham
Railways and Geology - a walk from North Walsham to Paston and Knapton. R.S. Joby
Report on Field Meetings to Wangford, and East Suffolk. P.G. Cambridge

No. 21 (April 1972) R.S. Joby
The History of the North Sea. B.M. Funnell
Geology in a College of Education. M. Bradshaw
The stratigraphical position of the Norwich Crag in relation to the Cromer Forest Bed Series. R.G. West
A preliminary account of a research borehole at Syleham, Suffolk. A.R. Lord
Report on a field meeting to the Norfolk coast at Yarmouth and Overstrand. S.J. Craig-Smith and G. Cambers
Report on a field meeting to the Norfolk coast (with the Conchological Society) P.G. Cambridge

No. 22 (September 1972) R.S. Joby
Mammals of the Last Interglacial in Norfolk. B. McWilliams
Lower Pleistocene molluscan assemblages and pollen from the Crag at Aldeby (Norfolk) and Easton Bavents (Suffolk). P.E.P. Norton and R.B. Beck
Geology at Gresham's School. R. Coleman
Books for studying G.C.E. and C.S.E. Geology. R.S. Joby
Report of field meetings at Hunstanton and West Runton. P.G. Cambridge

No. 23 (April 1973) R.S. Joby
A state of confusion in Norfolk Pleistocene stratigraphy. R.G. West
A possible mechanism for involutions in the Nar Valley. H. Evans
The base of the Carstone at Hunstanton. R.W. Gallois
Earth Science teaching at the Open University. R.C.L. Wilson

No. 24 (September 1973) R.S. Joby
Eaton Chalk pit - site of special scientific interest. R.J. Hornby, J.G. Goldsmith and J.C. Goff
Shingle Street, Suffolk: an analysis of a geomorphic cycle. R.E. Randall
Environmental geology of Sheringham. B.M. Funnell

No. 25 (June 1974) R.S. Joby
The place of early collectors in the development of geological studies in Norfolk. B. McWilliams
Earth and life sciences in Adult Education. R.E. Randall
The geology of the Ely district. R.S. Seale
Map of the geology of the Ely district. R.S. Seale

No. 26 (September 1974) R.S. Joby
The nature and assessment of fieldwork in geology. D.B. Thompson
Notes on Hunstanton Red Rock fossils H. Le Strange

Bulletin (Nos. 1-35)

No. 27 (April 1975) R.S. Joby
The Sub-Mesozoic floor in Norfolk. P.N. Chroston and M. Sola
The base of the Carstone at Hunstanton beach - Part II. R.W. Gallois
A Barremian fauna from excavations at Hunstanton Beach. A.A. Morter
Field Meeting to Bramerton near Norwich, 14-15 September 1974. P.G. Cambridge
Fossil ice-wedge polygons at Corton, Suffolk. K. Gardner and R.G. West
The Contorted Drift of North Norfolk. P.H. Banham
The two-till problem in West Norfolk. H. Evans

No. 28 (April 1976) R.S. Joby
Distribution and lithology of Drift behind Sheringham, Norfolk. W.M. Corbett and C.A.H. Hodge
Norfolk sandy beaches: applied geomorphology and the engineer. K.M. Clayton

No. 29 (October 1977) P.N. Chroston
Distribution of loess in North East Norfolk. W.M. Corbett
Whatever happened to the Boytonian? A review of the marine Plio-Pleistocene of the southern North Sea basin. P.G. Cambridge
Sediments from Holkham Beach, North Norfolk coast. W.I. Oronsaye
On the occurrence of Colus ventricosus (Gray 1839), a prosobranch mollusc. T. Pain

No. 30 (August 1978) P.N. Chroston
The Pleistocene history of West Norfolk. R.W. Gallois
The influence of chalk fractures upon the valleys of North and West Norfolk. R. Toynton
The Pleistocene succession at Corton, Suffolk. W.K. Pointon
Report on a field meeting at Dobb's Plantation, Wroxham (TG 273158), September 1977. P.G. Cambridge
Deposits marginal to the Red Crag Basin. R.G. Dixon
Gravity measurements in the Wash by the University of East Anglia. M. Sola and P.N. Chroston
Marine Ostracoda from the Quaternary Nar Valley Clay, West Norfolk. A.R. Lord and J.E. Robinson

No. 31 (September 1979) P.N. Chroston
Palaeoenvironmental analysis of the Dobb's Plantation section, Crostwick. B.M. Funnell
Preliminary Holocene stratigraphy of Brancaster marshes. P. Murphy and B.M. Funnell
Age and correlation of Pleistocene deposits in West Norfolk. A. Straw
A frost crack system at Covehithe cliff, Suffolk. R.G. West
History and prognosis of subsidence and sea-level change in the lower Yare valley, Norfolk. B.M. Funnell
The Kimmeridge Clay in Norfolk. R.W. Gallois
Kimmeridge Crawl: field trip to West Norfolk. B.M. Funnell
Field Meeting at Bramerton Common. P.G. Cambridge

INDEX (1953-85)

No. 32 (September 1982) P.N. Chroston
Quaternary sedimentation in the Sizewell-Dunwich Banks area, Suffolk. B.J. Lees
A note on supposed Crag shells from the Kippett Hills, Aberdeenshire. P.G. Cambridge
Amino Acid ratios in Crag molluscs. A.M.C. Davies, A.M. Funnell and B.M. Funnell
Composition of Pre-Anglian Gravels in Norfolk. R.W. Hey
Composition and origin of Thetford Mineral Water. R.W. Raiswell and M. Tranter
Report on a field meeting to Bulcamp, near Blythburgh, Suffolk, July 21st, 1979. P.G.Cambridge

No. 33 (December 1983) B.M. Funnell and P.G Cambridge
A faunal correlation of the Hunstanton Red Rock with the contemporaneous Gault Clay, and its implications for the environment of deposition. J. Andrews
Observations on the stratigraphical range and morphology of the Cretaceous cribrimorph Bryozoan Ubaghsia crassa (Lang). P.S. Whittlesea
The occurrence of the Brachiopod genus Rugia Steinich in the Norwich Chalk. P.S. Whittlesea
The Crag of Bulcamp, Suffolk. B.M. Funnell
Debenham and Stradbroke, two Crag boreholes compared. B.M. Funnell and S.K. Booth
Preliminary note on the Foraminifera and stratigraphy of C.E.G.B. Sizewell boreholes L and S. B.M. Funnell
An interglacial site at Galley Hill, near St. Ives, Cambridgeshire. R.C. Preece and P.A. Ventris
Vertebrates from a new site at Coston, Norfolk. J.L. Lightwing

No. 34 "East Anglain Geology" (December 1984) B.M. Funnell and P.G. Cambridge
The Late Jurassic to Mid Cretaceous rocks of Norfolk. R.W. Gallois
A guide to the geology of South-East Suffolk. S.J. Mathers, J.A. Zalasiewicz and P.S. Balson
The Glacial geology of Norfolk. G.S. Boulton, F. Cox, J. Hart and M. Thorton
A guide to the Holocene geology of North Norfolk. B.M. Funnell and I. Pearson

No. 35 (June 1985) B.M. Funnell and P.G. Cambridge
Jurassic and Cretaceous deposits of Upware, Cambridgeshire. S.R.A. Kelly
Notes on Chalk fossils: 1. A temporary section at Bramerton, 2. The brachiopod Kingenella kongieli in the Norwich Chalk, 3. Bryozoan - "Algal" association from the Upper Campanian-Maastrichtian. P.S. Whittlesea
The Pleistocene birds of South-Eastern England. C.J.O. Harrison
Catton Sponge Bed S.S.S.I. preserved for posterity. N.B. Peake

Bulletin (Nos. 1-35)

ALPHABETIC INDEX of authors, subjects, fossil, place and stratigraphic names; by date-volume number-and page/s

Abbott, R.T. 1977-29-56/57

Abies 1957- 7- 2
1972-22-15
1972-21-20

Ablation Tills 1974-27-68

Abra 1972-22-17/23/24
1978-30-86
1979-31-6/7

Accum, F. 1982-32-63/69

Acer morispessulanum 1983-33-63/66/
67/70

Acesta aff *longa* 1975-27-94

Acheulean 1979-31-25

Acila cobboldiae 1977-29-37/41
1978-30-86
1979-31-75

Acle Slough 1976-28-44-45
46-48

Acropagia 1971-20-36

Acroteuthis 1984-34-15

Actaeon 1972-22-16

Actinocamax 1957- 6- 2
1971-20-26

Adams, G.S. 1974-26-27/43

Adams, S.J. 1978-20-37

Adams, T. 1978-30-111

Admiralty Charts 1973-24-17

Aeolian drift 1971-19-24/26/27
1973-24-43
1977-29- 4
1976-28-16

Aerial photographs 1971-19- 2
1976-28-52
1977-29-11/15

Aeromagnetic map 1974-27-11

Agassiz, L. 1974-25-12
1974-27-44/45
1979-31-72

Ager, D.V. 1984-34-14

Agropyron junceiforme 1984-34-130

Agrostis-festuca Grassland 1971-19-12

Aix 1985-35-60

Alabaster, C. 1979-31-20/25

Alauda arvensis 1985-35-64

Alberta 1974-27-56

Albian 1957- 7- 4/5
1969-17-10/13
1971-20-11
1973-23-31
1974-25-38
1983-33-3/7/11/
13/14/17/22

Alca torda 1985-35-58

Aldeburgh 1971-20-34
1972-21-18/19/
21/22
1973-24-29
1977-29-24
1978-30-79
1982-31- 2
1984-34-68/69/
70/75/82

Aldeby Series 1971-19-17/18/20
21/24/30
1972-22-11...31

Alderford Common 1982-32-51...59

Aldringham 1977-29-38
1982-32-42/44

Algae 1985-35-38

INDEX (1953-85)

Algal flat 1977-29-52

Ali, O.E. 1985-35-13/16/17/21

Allen, J.R. 1967-15- 3
1971-20-26
1978-30-70
1984-34-124

Allen, P. 1984-34-90

Allochthonous 1978-30-96

Alluvium 1965-13-5
1976-28-31-32-33

Alnus 1972-21-21
1972-22-15
1979-31-6/13
1984-34-86

Aloidis 1978-30-99

Aluminium 1971-19- 4

Alveoli 1971-20-27

Amauropsis 1978-30-87
1983-33-42

Amino acid 1982-32-39...50
1984-34-88

Ammonia 1978-30-118
1979-31- 1/2/7/8/13
1983-33-40/41/43/49/56/60/62

Ammonites 1957- 7- 5
1973-23-25/26
1974-26/47
1974-27-21/24/25/26/27/29/30/41
1979-31-55/60/69/70
1983-33-24
1984-34-20/31
1985-35-34

Ammonitico Rosso 1983-33-16

Ammophilia arenaria 1984-34-130

Amoeboceras 1979-31-52/55/56

Ampthill clay 1974-25-21/38
1979-31-65

Anadara diluvii 1977-29-33

Anaerobic 1971-19- 4

Anas 1985-35-58/59/

Anasca 1969-17-12

Ancylus 1969-18-17

Ancycloceras 1973-23-26/30

Anderton, R. 1983-33-14/22

Andrew, R. 1984-34-71/77

Andrews, J.T. 1971-28-38
1984-34-42/51

Andrews, Julian 1983-33- 3...36

Anglian Stage 1973-23-3/6/7
1973-24-37
1974-25-38
1974-27-52/74
1977-29-40
1978-30- 5/55/72
1979-31-17/22/24/33
1984-34-91/92/107

Angulus benedeni 1977-29-34

Anhydrite 1971-20- 9

Anisocardia 1985-35-14

Anmer 1978-30-39

Annelids 1985-35-37/40

Anomalosipho 1977-29-41

Anomia sp.	1971-20-35 1972-22-16/23 1974-27-29 1978-30-86/98 1979-31-75
Anser	1985-35-59/62
Ant, River	1971-20-32
Antalis	1975-27-29
Antarctica	1962-11- 7
Antian	1972-21-20 1972-22-11/12/13/22/28/29 1982-32-44/48 1983-33-35
Antwerp	1977-29-25/29/31/34/38
Anversian	1977-29-25/30
Apodemus	1972-22- 5
Aptian	1957- 7- 4 1973-23-26/30/31 1974-25-38 1974-27-30 1983-33-22/35/43/54 1985-35-19
Aranaruchapun, S.	1976-28-67
Arboreal pollen	1972-22-15
Archaeological observations	1971-19-32
Arctic freshwater bed	1965-13-1/2 1968-16-1 1972-21-17 1973-23-3 1977-29-37
Arctic Ocean	1977-29-41
Arctica islandica	1971-20-36 1972-21-2/42 1974-27-42 1977-29-40 1983-33-42
Arctica islandica (cont)	1978-30-86 1979-31-5/75
Arderon, W.	1974-25-5
Arenicola	1978-30-96/101
Arenobulimina	1983-33-7/11/13 24/26
Aristotle	1974-25-3
Arkansas	1969-17-13
Arkell, W.J.	1985-35-10/11/17
Armco culvert	1976-28-40
Artesian	1976-28-44
Asciphora	1969-17-12
Ash	1973-24-9
Ashley Series	1971-19-20/21/30
Ashwicken	1978-30-18
Aspidoceras sp.	1979-31-55/56/65
A.E.B.	1974-26-10
Association of Teachers of Geology	1972-21-12/15
Astarte	1972-21-41 1972-22-16/23/26 1975-27-29 1977-29-33/34/41 1978-30-86/99/100 1979-31-5/57/75
Astbury	1974-25-33
Aster	1979-31-11
Astrova, G.C.	1969-17-11
Atherfield clay	1973-23-26

INDEX (1953-85)

Atlantic 1972-21-2/3/7/8
1979-31-13

Audley-Charles, M.G. 1971-20-38

Aulascostephanus 1979-31-52/54/55/56

Autissiodorensis 1979-31-57

Avon, River 1961-10-11
1965-13-5/6

Aylsham 1978-30-77
1979-31-24
1984-34-107

Aythya fuligula 1985-35-59

Azolla filiculoides 1957-7-2

Babingley, River 1978-30-8/15/16
1984-34-14/15/27

Bacton 1968-16-3

Baden-Powell, D.F.W. 1956-5-6
1957-7-1/3
1968-16-7/8
1972-22-2
1973-23-6/8
1974-25-24/33
1974-27-63/74
1978-30-31/36/55/75/80/90
1979-31-17/23/26/28
1984-34-71/77

Baginton sand and gravel 1965-13-5

Bain Valley 1979-31-21/22

Baker, H. 1974-25-5

Baker, H.W. 1982-32-24/27/29

Baker, R.E. 1973-24-16

Balanaglossus 1971-20-36

Balanophylia 1978-30-101

Baltic Sea 1974-27-55/56

Balanus 1978-30-87
1979-31-41/76

Balson, P.S. 1984-34-65...101

Bamber, R.N. 1982-32-23

Banham, P.H. 1961-10-1...13
1962-11-1...16
1965-13-7/8
1968-16-3/10/11
1971-19-35...38
1971-20-38
1973-23-5/9
1975-27-55...60
1976-28-4/21/25
1978-30-38/55/58/66/72/75
1984-34-111

Barbatia 1985-35-15/17

Barford 1973-23-4/6

Barnacles 1974-25-11
1974-27-36/43
1978-30-95

Barningham 1976-28-3

Barrell, J. 1967-15-1...6

Barremian-Albian sequence 1973-23-30/31
1974-27-21/26/29/30
1975-27-21...27
1984-34-29

Barren red measures 1974-27-8

Barrett Ringstead Stream 1973-23-32

Barton Bendish 1978-30-50

Barton Mills 1969-17-9
1971-19-42

Basal nodule bed 1977-29-27/33

Basaltic rocks 1971-19-33
1979-19-33

Bascomb, C.L.	1977-29-21
Basement bed	1971-19-32
Basement till	1978-30-29
Bassett, D.A.	1974-26-6/27/ 32/39
Bassett, M.G.	1974-25-4
Batrachopora crassa	1983-33-27
Bats	1973-24-8
Battacharyya, G.	1984-34-124
Batter slopes	1976-28-36/42
Battisford	1978-3-93/95.. 97/102..104
Baventian	1972-21-18/20/22 1972-22-11...13/ 15/21/22/28 1977-29-28 1978-30-93 1979-31-31 1982-32-48/55 1983-33-54 1984-34=89
Bawdsey	1961-10-11 1973-24-16 1977-29-26 1982-32-39/42
Bawsey	1974-27-61/64/66 69/71 1979-31-18/20/21
Bear	1972-22-8
Beaumont, P.	1966-14-2
Beauvais, L.	1985-35-17
Beccles	1969-17-3...6 1971-19-2/14/17 21/24/30 1977-29-9
Beck, R.B.	1972-21-7 1972-22-11...31 1982-32-44
Beck, R.B. (cont)	1983-33-45/48 1984-34-80/82
Beck Row	1974-25-23
Bedford rivers	1974-25-21/25/28 30 1976-28-33
Beer axis	1957-7-3
Beeston Hill	1968-16-3 1973-24-41/43/44 1982-32-55 1985-35-44/45
Beestonian	1969-18-11 1972-21-17/18/20 22 1972-22-12 1978-30-92 1979-31-33 1983-33-27
Beetley	1969-18-17..19 1972-22-2...4 1973-23-5 1979-31-25
Beik, R.B.	1972-21-9 1978-30-103
Belaugh	1978-30-77
Belemnite	1971-20-26 1972-21-43 1973-24-5/7 1974-26-47 1974-27-31/41 1978-30-95 1979-31-55 1983-33-27/29/ 32 1985-35-34
Belemnitella	1957-6-1...4 1985-35-39/45
Belemnitella mucronata	1968-16-17 1969-18-6...12
Belfast	1967-15-2
Belgrandia marginata	1983-33-69

INDEX (1953-85)

Belgium 1972-21-3/7
1977-29-4/27
1984-34-77
1985-35-50/71

Bell, A. 1977-29-34
1984-34-69/78

Bell, F.G. 1974-25-34
1978-30-36

Bell, S.V. 1959-9-1...4

Bellerwell 1974-27-11

Belvoir, Vale of 1979-31-20

Benacre 1972-21-31

Benavides-Caceres, V.E. 1967-15-5

Bennison, G. 1972-22-40

Benwick Mere 1974-25-29

Bering Sea 1977-29-41

Beringius turtoni 1978-30-84/87

Berms 1976-28-36

Betula 1972-21-21
1972-22-15
1984-34-86

Bingley, F.J. 1973-24-32

Binnies & Partners 1978-30-111

Bioclastic reef facies 1985-35-24

Bioherms 1971-20-21

Bioturbation 1979-31-31

Biozones 1977-29-32

Birch 1973-24-9

Birds 1985-35-53...70

Birmingham 1965-13-4...7

Bishop, B.C. 1962-11-8

Bishop, W.W. 1978-30-38

Bison 1969-18-18
1972-22-4/5/8
1982-32-51...59
1983-33-77

Bituminous pelmicrite 1985-35-24

Bivalves 1971-19-33
1972-21-2
1972-22-22
1973-23-29
1974-27-25/29/34
1979-31-55
1984-34-20/31
1985-35-34/40

Bixley Heath, Ipswich 1971-19-33

Black, M. 1959-9-3
1983-33-6

Black, R. 1961-10-1

Blackborough End Pits 1973-23-11/12/
23/31
1974-27-26
1978-30-11/31

Black Dyke Farm 1969-17-7/8
1974-25-23
1978-30-52

Blackstone Dorset 1979-31-46/62

Blackthorn 1973-24-9

Blake, J.F. 1985-35-9...11

Blake, J.H. 1963-12-4
1969-17-4
1974-27-47/53
52
1978-30-55/75
1982-32-51

Blakeney 1973-23-7
1984-34-126...
128/136

Blake's Pit, Bramerton 1969-17-6; 1974-27-33..45; 1978-30-84; 1979-31-6...8/

Block faulting 1971-20-8

Bloom, B.S. 1974-26-27/31/44

Blue till 1974-27-61/63/64/66/71

Blyth, River 1982-31-2/71/72; 1983-33-35

Boatman, A.R.C. 1984-34-84

Bob Hall's Sand, Wells 1976-28-58

Boillot, G. 1972-21-4/6/9

Bollen, F.A. 1974-26-44

Bones and teeth 1971-19-33; 1974-27-39; 1979-31-76

Bonney, T.G. 1962-11-12; 1985-35-6/9/18

Boom, Belgium 1977-29-30

Booth, S.K. 1983-33-45...53

Boreal 1972-21-8; 1972-22-20; 1979-31-13

Boreholes 1966-28-33/35; 1971-19-39; 1974-27-3/4/5/9/17/26/30; 1979-31-11/46/48/49/55

Boreoscala 1974-27-41; 1977-29-40; 1978-30-87; 1979-31-76

Börner 1972-22-41

Borrow Pit 1972-24-19

Bos primigenius 1972-22-4/8

Boston 1978-30-11

Boswell, P.G.H. 1954-2-3; 1956-5-1; 1962-11-12; 1971-20-26/27; 1974-25-23/34; 1976-28-4/6/26; 1978-30-93/97/10; 1984-34-11/14/71, 77

Bottisham Fen 1985-35-16

Bouguer anomoly 1974-27-12/16/17

Boulder clay 1968-16-1; 1971-19-17/20/24 27/30/39/41; 1972-21-26/41; 1973-23-3/7/8; 1974-25-24/38; 1974-27-47; 1976-28-3/12/20/21/30/32/38/44/4; 1977-29-49; 1978-30-39; 1984-34-106

Boulton, G.S. 1974-27-63/74; 1978-30-67/68/75; 1984-34-103..122

Bouysse, P. 1972-12-6

Boxstones 1977-29-25/33

Boxted 1978-30-97

Boylan, P.J. 1974-25-11; 1978-30-29..36

Boytonian 1977-29-23..45

Brachiopods 1955-3-5; 1969-18-6..12; 1971-19-41; 1971-20-21; 1974-27-7/25/19/39; 1979-31-55; 1983-33-32; 1985-35-36/40

INDEX (1953-85)

Bracondale 1954-2-2/3

Bradfield, J.M. 1974-26-27/44

Bradshaw, M.J. 1972-21-11..15
1972-22-39/40
1974-26-6

Bradshaw, R. 1973-23-16

Brady, G.S. 1978-30-117

Bramerton 1969-17-6
1974-25-8
1975-27-33..45
1977-29-26/38/42
1978-30-85/88
1979-31-6/7/8/33/71
1982-32-42/44/45/48/54/55
1983-33-35/43/54
1984-34-86
1985-35-39...46

Bramford 1971-20-26/27
1978-30-92/95

Brancaster 1979-31-11...16
1984-34-126/127 131/133

Brandon 1965-13-5

Branscombe axis 1957-7-3

Branta leucopsis 1985-35-62

Breccia 1973-23-25

Breck 1971-19-40

Breckland 1961-10-10/11
1971-19-2/27/30 31/39...42
1973-23-3
1974-25-26
1979-31-24

Breckles 1979-31-49

Brereton, J. 1977-29-21

Brest 1972-21-3

Brickearth 1953-1-5
1968-16-18/19
1969-18-4/5
1971-19-24/29
1973-23-3
1974-25-10/24/25
1974-27-47
1976-28-6/7/16/17 20/25/30/38/41
1977-29-3
1978-30-31

Brick making 1979-31-45/48/64/66

Brick Kiln Dale 1974-27-56

Bridge Pit North 1985-35-23/25

Bridgham 1971-19-39

Bridlington Crag, Dimlington 1977-29-57
1978-30-117

Brighton, A.G. 1973-24-8
1985-35-6/13/22

Bristow, C.R. and Cox, F.C. 1973-23-6/7/8
1976-28-21/26
1984-34-66/116

B.A.A.S. 1974-26-5
1984-34-107/124

British Industrial Sands 1974-27-61
1984-34-23

British Museum 1971-19-41
1973-23-30
1974-27-24

Briton's Lane Gravels 1971-19-37
1973-24-37...44
1974-27-56/58

Broads 1976-28-30
1979-31-35

Bromley, R.G. 1983-33-17

Bromwich, J.I. 1974-25-35

Bronze Age 1974-25=28

Broome 1974-27-44

Brown, B. 1955-3-1...4; 1955-4-4/5

Brown, G. 1974-25-30/34

Brown earth 1971-19-29; 1973-24-43

Brown drift 1976-28-4/6..10

Browne, Sir Thomas 1974-25-4

Bruckshaw, J.M. 1974-27-17

Brumer, J.S. 1974-26-44

Brunstrom, R.G.W. 1970-20-6/8/13

Brushwood peats 1971-19-17

Brydone, R.M. 1955-3-5; 1957-6-1; 1962-11-12; 1971-20-26..28

Bryophytes 1976-28-44

Bryozoans 1956-5-3; 1959-9-2; 1969-17-10//15; 1972-21-3/4; 1983-33-27..31; 1985-35-37/40

Bubo bubo 1985-35-53/55/69

Buccella 1979-31-2/9; 1983-33-40/57/60/62

Buccinum 1972-22-22; 1974-27-71; 1984-34-85

Bucephala clangula 1983-33-42; 1985-35-59

Buckenham Tofts 1971-19-39

Buckinghamshire 1979-31-45

Buckland, W. 1974-25-6/11

Bulcamp 1982-32-42/44/71/72; 1983-33-34...44

Bulimina 1983-33-60

Bulk fill 1976-28-29

Bullard, E.C. 1956-5-1; 1974-27-3/4; 1985-35-6

Bullockyard Pit 1985-35-47

Bungay 1972-21-18/22; 1977-29-7

Bungenstock, H. 1971-20-13

Bunter Pebbles & Bunter Sandstone 1971-20-3/8/9; 1974-27-5; 1978-30-19; 1982-32-55

Bure Valley 1972-21-29; 1976-28-46; 1977-29-37/44; 1978-30-77/79...91; 1979-31-35

Burgh Castle 1963-12-1...4; 1974-25-7; 1978-30-61

Buried channels 1978-30-40/49/50/53

Buried valleys 1978-30-15/40/49; 1979-31-19

Burn, R. 1978-30-50

Burnham Overy 1977-29-46; 1978-30-49

Burnt Fen 1974-25-23/26/30

Burnt Hill 1974-25-22

Burrow-mottled 1973-23-29; 1974-27-24/25

Burrows, H.W. 1984-34-69/77/85

Burystead Farm, Sutton 1974-25-21

Butcher's Hill 1974-25-29

Buteo buteo 1985-35-58

Butley 1971-20-35 1977-29-25/27/34 36/41/44 1982-32-42 1984-34-85

Butrym, J. 1968-16-18

Butterfly bones 1974-27-44 1977-29-38

Butterwick 1978-30-111

Bythinia 1969-18-17

Caenozoic 1969-17-13

Caister-on-Sea 1953-1-5 1972-21-32/34 1976-28-61

Caistor St. Edmunds 1955-3-1 1957-7-1 1969-18-8/11 1977-29-26/28

Calabrian 1957-7-1

Calcareous soils 1971-19-9 1974-27-64/69

Calcium carbonate 1978-30-66/67

Caledonian 1974-27-3/12

Calcicolous grass 1971-19-12

Calcethorpe 1979-31-21/24/25

Caledonian Mts. 1971-20-4

California Gap 1972-21-41 1977-29-41

Callihoplites auritus 1983-33-11

Calliostoma 1978-30-87

Callista 1978-30-99

Callomon, J.H. 1985-35-6/11

Calluna 1971-19-12

Calluna vulgaris 1971-19-41

Calthorpe 1976-28-6

Calyptraea 1971-20-35 1972-22-20/22 1974-27-42 1977-29-41 1978-30-98 1979-31-6/7/76

Cam, River 1978-30-11/15/31

Cambers, G. 1972-21-29...40 1976-28-60/62/67 1984-34-124

Cambridge 1969-17-13 1974-25-25/29 1974-26-10 1974-27-4/7/9/10 11/33 1979-31-45/49

Cambridge, P.G. 1969-17-6...9 1971-20-34...36 1972-21-41...43 1972-22-20/26/43 44 1975-27-33...45 1977-29-23...45/ 56 1978-30-77...91 113/118 1979-31-1/10/73 74/77 1982-32-37/38/71/ 72 1983-33-63 1984-34-77/84

Cambridge Sub-Dept Quaternary Res. 1972-22-4/5

Cameron, R.L. 1962-11-7

Campbell, R.M. 1973-23-16/23

Canada 1977-29-24

Candidula crayfordensis 1983-33-63/6

Cannon Shot Gravels 1969-18-17
1973-23-7

Cantley Pit 1983-33-27

Capulus 1978-30-98

Carbon tetrachloride 1979-31-1

Carbonate 1978-30-64

Carboniferous limestone 1971-20-2
1974-27-4/8/9/11
1979-31-24

Carcharodon megalodon 1977-29-33

Cardiaster 1974-26-48

Cardiocerus cordatum 1984-35-11

Cardita 1978-30-99/100

Cardium 1957-7-1
1972-21-42
1972-22-17/23/24
1974-27-36/71
1977-29-40
1978-30-97/102

Cardium angustatum 1977-29-36/37/40

Carey 1973-24-17

Carinocythereis 1978-30-114/116

Carneithyris 1957-6-1
1969-18-10
1973-24-7
1985-35-42

Carpinus 1957-7-2
1972-21-20/21
1972-22-15
1979-31-6

Carr, A.P. 1972-21-31/38
1973-24-16/21/23 28/30

Carr, A.P. (cont) 1982-32-2/27/29 30
1984-34-75

Carreck, J.N. 1971-20-37

Carstone 1957-7-4
1973-23-11...34
1974-25/22/38
1975-27-21...27 61/64
1978-30-5/14/19 22
1979-21-20
1983-33-3/11
1984-34-21...23

Carter, D.J. 1984-34-71

Cartwright, L. 1979-31-16

Carynx hippo 1977-29-38

Casey, R. 1967-15-3
1973-23-26/30/34
1974-26-47
1974-27-27
1984-34-6/8/14 20/26/34
1985-35-18

Cassidulina laevigata 1983-33-48/60/62

Castle Rising 1978-30-10

Castle's Farm 1974-25-23

Castor 1978-30-95

Catt, J.A. 1974-27-71/75
1977-29-4/5/9/21
1978-30-29.36
1979-31-25

Catton Grove 1968-16-17
1969-18-11
1985-35-71/72

Cawston 1979-29-9

Cayeux, L. 1959-9-3

Cellepora 1985-35-45/46

INDEX (1953-85)

Cementations 1979-31-51/54/58/60/65/69

Cenomanian 1957-7-5
1967-15-2/3/5
1969-17-12...14
1974-25.38
1983-33-6/7

Central Trough 1972-21-4

Cephalopoda 1985-35-40

Cepphus 1985-35-57

Cerastoderma edule 1978-30-86/98
1979-31-4/6/8/13/75
1983-33-41...43
1984-34-132

Ceratophyllum 1983-33-64

Cerithium tricinctum 1983-33-41...43

Cervid 1978-30-87

Cervus elephas 1969-18-18
1972-22-4/8
1978-30-95

Cetacean 1977-29-35

Chalcedony 1979-31-76

Chaldron 1973-24-4

Chalk 1953-1-7
1955-3-5
1957-6-1...4
1962-11-14
1963-12-4...7
1965-13-1/2/7/8/9
1968-16-17/19
1969-17-4/5/7
1969-18-6...12/14/15
1971-19-6/9/30/35/40/41
1971-20-26...29
1972-21-3/4/6/34
1973-24-5/28/37/41
1974-25-23/26

Chalk (cont) 1974-27-33/34/37/61/63/65
1977-29-29/39/40
1978-30-8/14/30/39..54/67/77/81/90/92/95/97/103
87-fossils
1979-31-2/8/9/15/18...20/22
1982-32-20/53
1983-33-3/20/27/32
1984-34-132
1985-35-39...46/71/72

Chalky Jurassic Clay 1971-19-35/36
1978-30-3/14...16/18/19/29...31/83
1979-27-29

Chamosite 1973-23-29

Channel Islands 1972-21-3/4

Channel Sands 1984-34-128

Chapman, V.J. 1984-34-124

Charixa 1969-17-12

Charlesworth, E. 1974-25-8/12
1984-34-69/78/84/99

Charlesworth, J.K. 1974-27-50/59

Charlton axis 1957-7-3

Charophyte Oogonia 1978-30-113

Chatter Marks 1974-27-34
1978-30-81

Chatteris 1974-25-33

Chatwin, C.P. 1961-10-12
1966-14-2
1978-30-97/103
1985-35-6

Cheetham, A.H. 1969-17-13

Cheilostomata 1969-17-10/11/13/15

Chelford 1965-13-5

Cheloniceras 1973-23-25/30 1974-27-24

Chenopodiaceae 1972-21-21

Chert 1982-32-55

Cheshire plain 1965-13-5/6

Chet, R. 1976-28-38

Chettisham 1974-25-24

Chillesford 1953-1-6 1955-4-1/3 1971-20-35/36 1972-21-18/19 21/22 1977-29-27/37 1978-30-79 1979-31-72 1982-32-42/47 1984-34-82/86

Chilterns 1978-30-14

Chiswick 1979-31-62

Chiton valve/plates 1972-22-22 1979-31-76

Chlamys 1972-22-22 1974-27-30 1978-30-48/84 1979-31-5/75 1985-35-15

Chondrites 1969-17-92 1984-34-18

Christ, C.L. 1982-32-67

Chroston, P.N. 1975-27-3...19 1978-30-105..112 1985-35-6

Chrysallida 1972-22-16

Chrysophrys 1978-30-87

Cibicides 1979-31-1/2/4 7...9 1983-33-40/43 56/57/60/62

Ciconia ciconia 1985-35-62

Cidarid 1974-26-48 1978-30-95

Circles 1961-10-5/6

Circular arc type failure 1967-28-40

Clacton-on-Sea 1957-7-2 1972-21-8

Clangula 1985-35-57

Clapham, A.R. 1983-33-64

Clark, J.G.D. 1974-25-28/34

Clark, J.W. 1985-35-3

Clarke, J.E. 1976-28-67 1979-31-69

Clarke, K.B. 1972-21-28

Clarke, R.R. 1972-22-6

Clathrus 1972-22-16/22

Claxby Beds 1984-35-22

Clay 1954-2-2/3 1955-4-1/3/4 1963-12-1/2 1966-14-1/2 1967-15-5 1969-17-3...5 1969-18-13...16 1971-19-9/17/24 30/32/41 1971-20-9 1972-22-12/21 1973-23-25/26 1973-24-37/41 1974-25-21 1974-27-8/21/24/ 26/31/34/36/39/ 41/67 1976-28-35/38 1977-29-20/25 1978-30-14/16/17 24/31/58/61/64 66/72/79/97 1979-31-18...26/ 45...66

Clay (cont) 1983-33-3...26 1985-35-21
Claydon Church Lane 1971-20-26
Clayton, K.M. 1971-20-18/25 1976-28-49...67 1977-29-46/55 1984-34-124
Cleithrum 1974-27-44
Clethrionomys 1972-22-5
Cley 1969-18-11 1984-34-131/139
Cliff falls 1972-21-37/38 1976-28-56
Clifford, M.H. 1974-25-27/28
Clifton Park, Cromer 1971-19-35
Cliona sp. 1978-30-87 1979-31-76
Clyde Beds 1974-27-42
Clymo, R.S. 1982-32-62
Coal 1966-14-2 1971-20-3/4 1974-27-25/26 1978-30-19/22 1979-31-63
Cobb, R.T. 1973-24-16/19/21/32
Cobbles 1973-23-15/16 22
Coccolith 1979-31-60
Cochlodesma 1972-22-15/17/23
Cocinnithyris 1957-7-6
Cockley Cley 1978-30-50
Coelopora 1985-35-46
Coelosmilia granulata 1983-33-29
Coffer Dam 1976-28-39
Coleman, R. 1972-22-33...38
Coles, B.P.L. 1979-31-35/44 1982-32-29
Coles, J.M. 1974-25-31...34
Collectors 1974-25-3...14
College of Education 1972-21-11...18
Collette, B.J. 1971-20-13
Collins, J.I. 1971-20-38
Collyweston Beds 1967-15-2
Colne 1974-25-25
Colney 1968-16-17...21
Coltishall 1978-30-77
Colus ventricosus 1977-29-56/57
Comanchean 1969-17-13
Commissioners' Pit 1985-35-20
Common Pit, Bramerton 1974-27-36 1979-31-71
Compass clinometer 1978-30-43
Compositae 1972-22-5/15
Conaco Limited 1974-27-17
Conchological Society 1972-21-41
Concrete aggregates 1976-28-29
Concretions 1971-19-33 1973-23-29 1974-27-22/26
Cone-in-cone 1979-31-69

Congham	1978-30-10
Conifer	1969-18-18 1984-34-125/131
Continental Drift	1971-20-22 1976-28-55
Conulus	1969-17-9
Cook, E.E.	1971-20-13
Cook's Tour Geology	1974-26-7
Cooper, B.	1971-20-13
Coprolite	1977-29-35 1985-35-23
Coralline Crag	1956-5-2 1957-7-1 1969-17-11 1971-20-35/36 1972-21-3/6/22 1974-25-8/38 1977-29-24/25 27/28/32...34 43...44 1978-30-80 1982-31-2/12 14/15 1984-34-66...70 1985-35-47...51
Corals	1971-20-21 1985-35-21/37 41...51
Corbett, W.B.	1971-19-2...31 1971-20-28 1973-24-44 1974-25-26/34 1976-28-3...27 1977-29-3...22
Corbicula	1971-20-34 1977-29-38...41 1982-32-41/46
Corbula	1972-22-17/19 23/24/26/27 1974-27-31 1978-30-86 1979-31-6 1982-32-38
Cores	1978-30-85
Corpusty	1976-28-20
Corte, A.E.	1973-23-23
Corton Sands/ Cliffs	1956-5-6 1963-12-1...4 1965-13-2 1971-19-17 1972-21-17/26/ 41/42 1973-23-3/4 1975-27-47...53 1978-30-55...76 1984-34-108/109
Corylus	1957-7-2
Coscinopora	1985-35-39
Costessey	1954-2-5
Coston	1983-33-73...80
Cotentin Peninsula	1972-21-4
Cottenham Series	1974-25-22
Coturnix	1985-35-61
Coughlan, J.	1982-32-23
Course unit	1973-23-45
Covehithe	1974-27-44 1977-29-26/28/38 1979-31-31...34 1982-32-48
Coveney	1974-25-21
Cover loam	1976-28-14/16..1 25 1977-29-4
Cowries	1972-21-2
Cox, B.M.	1973-23-5/7/8 1976-28-6/21/26 1978-30-13 1985-35-6/10
Cox, F.	1984-34-103..122
Cozens-Hardy	1984-34-124

Crag 1953-1-6
1954-2-2
1955-3-1/2
1955-4-1...4
1957-6-1
1957-7-1
1968-16-18
1969-17-3...6/10/11
1969-18-4/5/14...16
1971-19-17/32/33
1971-20-34...36
1972-21-3/6/7 17...23.41.42
1972-22-11...31
1973-23-3
1974-25-8
1974-27-33.37 41...43
1976-28-41/46
1978-30-39/40 77/79..81/83..85 88/92
1979-31-1..10/71
1982-32-20/37.. ..50/53/72
1983-33-35...53 57
1984-34-66...90

Craig-Smith, S.J. 1972-21-29...40
1976-28-67

Cranbrook, Lord 1971-20-38

Cranmoor Lots 1974-25-30

Cranwich Heath 1978-30-50

Creber, G.T. 1984-34-14

Creeting St, Mary 1971-19-33
1978-30-92...95

Cretaceous Rocks 1957-7-3...6
1959-9-1...4
1967-15-4
1969-17-7/11/13/15
1969-18-7
1971-20-6/8..11
1972-21-2
1974-25-22/23
1974-27-56
1978-30-5/67/74

Cretaceous Rocks (cont) 1979-31-18/20/21/22/24/25/49
1983-33-32
1984-34-3...6
1985-35-3...3

Cretirhynchia 1957-6-1
1968-16-17
1969-18-6...9
1973-24-7

Cribrimorpha 1969-17-12

Cringleford by-pass 1976-28-41/42

Crioceratid 1973-23-32

Crinoid 1971-20-21
1978-30-95
1985-35-37

Crinoidal chert 1974-27-41
1978-30-83

Cromer Forest Bed 1955-4-4/5
1956-5-6
1957-7-2
1965-13-1...4
1972-21-7/17..23
1973-23-3
1974-27-47..53/57
1978-30-57
1985-35-57

Cromer Ridge till 1961-10-12
1968-16-1/9/10
1971-19-2/24/27 30/36
1972-21-17/35
1973-23-3
1973-24-37/43
1974-27-56/57
1976-28-3/10/18 59/61
1977-29-3..11/46
1978-30-58/64/70 72

Cromerian 1972-21-17/20/42
1972-22-12
1973-24-43
1977-29-28/39

Cross Bank 1974-25-28

Cross bedding	1973-23-13/15 1974-27-25
Cross, H.	1982-32-66/69
Crossley, J.D.	1974-26-44
Crostwick	1979-31-1...10 1982-32-39/42
Crowfoot	1972-22-12
Crowland	1978-30-11
Crustacean	1971-19-32 1971-20-35 1978-30-87 Claws 1979-31-56/57 1985-35-37
Cryoturbation	1969-18-18 1972-22-2 1978-30-24
Cryptostomata	1969-17-11
Crypts	1974-27-34
C.S.E.	1972-22-33...42 1974-20-8/27/32 39
Ctenostomata	1969-17-10/15
Culford	1974-27-4/9/11 1979-31-49 1985-34-16
Cuestas	1972-21-3/6
Curray, J.R.	1978-30-57/75
Current bedding	1971-20-35
Current marks	1977-29-52
Curry, D.	1984-34-80
Curtis, C.D.	1982-32-63
Cuttings	1976-28-29
Cyanopica cyanea	1985-35-60
Cyclocardia	1977-29-34
Cyclostomata	1969-17-11/14
Cygnus	1985-35-58/63
Cylichna	1979-31-7
Cymatoceras	1974-26-47
Cyperaceae	1972-22-15
Cyprina	1955-4-4 1972-22-15/16/19/23/24 1978-30-90
Cythere	1978-30-15
Cytheridea punctillata	1978-30-115
Dainton Report	1971-20-18/25
Dalton, W.H.	1984-34.69
Dama dama	1972-22-5
Danish	1972-22-26 1974-27-55
Darcy Lode	1974-25-32
D'Arcy Exploration Co	1974-27-5
Darwin, C.	1974-25-11
Davies, A.M.C.	1982-32-39...50 1983-33-43
Davies, H.	1976-28-16 1977-29-22 1978-30-66/76 1984-34-106
Deavin, P.	1976-28-48
De Bakker	1976-28-20/26
Debenham	1983-33-45...53
Decalcification	1971-19-4 1971-20-35/36 1974-27-26/41 1977-29-28/34 1978-30-96/97 1979-31-4/12/17

Decollemont 1962-11-5/6

Deegan, S.E. 1978-30-38

Deer 1969-18-18
1972-21-42

De Jong, T. 1974-27-59

Delta 1967-15-5

Deltoideum 1979-31-65

Denchworth Series 1974-25-21

Denmark 1972-21-2/7
1973-23-8
1978-30-117

Denver Sluice 1979-31-49/50
58/69

Dermal Ossicles 1974-27-44

Dersingham and Denver 1957-7-5
1978-30-8
1984-34-11/22
26/27

Desnoyers, M. 1984-34-69

Deurnian 1977-29-25

Devensian 1973-23-3/7
1974-25-28
1976-28-25
1977-29-4/11
1979-31-17/9
22/24/25
1983-33-63

Devonian 1967-15-3/5
1974-27-4/7/9
10/11

Dhonau, T.J. 1974-27-55

Diapir 1971-19-36
1971-20-6
1974-27-58
1977-29-27

Diatoms 1972-21-26

Diestian 1956-5-1/2
1977-29-33

Dimlington 1978-30-30

Dimmocks Cote 1974-25-28
1985-35-17

Dimorphoplites niobe 1983-33-7

Dines, H.G. 1978-30-97/103

Dingle, R.V. 1971-20-15

Dinham, C.H. 1974-25-25/32/34
1983-33-64

Dinoflagellates 1979-31-51

Diodora 1978-30-98

Diomedea albatrus 1985-35-57

Diorite 1974-27-4

Diploceras Cristatum 1983-33-7/11

Diplodonta 1972-22-23

Dips 1978-30-47

Discinisca 1979-31-57

Diss 1979-31-24

Ditrupa 1956-5-2
1978-30-101

Divaricella 1978-30-86
1979-31-75

Dixon, R.G. 1978-30-92...104
1979-31-81
1984-34-75/84

Dobb's Beck 1978-30-77

Dobb's Plantation Wroxham 1978-30-77/78/84
85/89
1979-31-1...10
1982-32-44

Dobrin, M.B. 1978-30-109/111

Docking 1972-22-43
1979-31-21

Dogger Bank 1972-21-8

Doggers 1974-27-63
1979-31-51/53/54
60/65/69

Dolerite 1979-31-18

Dolomitic limestone 1971-20-9
1974-27-8

Dolphins 1977-29-39

Domburg, Zeeland 1977-29-38

Domes 1971-20-9

Don, R. 1974-25-3

Donax 1971-20-34
1972-22-15/17/19
1978-30-86
1979-31-6

Donkey Lane 1973-24-4

Donner, J.J. 1957-7-2
1961-10-13
1962-11-8/10
1965-13-7
1968-16-10
1973-23-6/24
1975-27-69/75
1978-30-58/76
1979-31-19/23
1984-34-107

Donovan, D.T. 1971-20-13

Doppert, J.W.C. 1985-35-47...51

Dorset 1969-17-13
1979-31-45/56

Dosinia 1978-30-99

Double, I.S. 1978-30-97

Downham Market 1978-30-14
1979-31-5/57/61
62/64/69
1984-34-11/17

Dowson 1972-22-12

Drab 1978-30-29/30

Dragfolding 1971-19-36

Drainage 1971-19-6
1976-28-35/36

Drake, L. 1975-27-65/74

Drayton Pit 1969-18-11
1973-24-37

Dreimanis, A. 1975-27-68/71/74
1978-30-75

Drente Formation 1972-21-8

Drift, Soil 1968-16-1
1971-19-6/9/24
35/39
1974-25-23/25
1975-27-55...60
1976-28-3...27
32/33
1978-30-93

Drowned Valley 1972-21-6
1975-27-38

Drury, G.H. 1973-24-15

Dry Valleys 1971-19-6/9
1977-29-17
1978-30-40

Dubourdieu, G. 1967-15-5

Duffey, J. 1974-26-44

Dufrendyia 1973-23-30
1975-27-24

Duigan, S.L. 1957-7-2
1965-13-1

Dunchurch 1965-13-5

Dune bedding 1978-30-61
1984-34-125/130

Dunham, K.C. 1971-20-37

Dunsmore gravel 1963-15-4

Dunwich 1982-32-1/4/8

INDEX (1953-85)

Durham	1966-14-1...7
Dzulynski, S.	1973-23-22/23
Earith	1974-25-25 1978-30-31
Earl, Mr.	1974-25-10
'Earth materials'	1973-23-36
East Anglian Brabant massif	1956-5-1
Earth Sciences	1974-25-15...19
East Anglian trough	1972-21-4
East Beckham	1976-28-10
East Dereham	1972-22-4 1976-28-43/44
East Frisian Islands	1973-24-29
East Harling	1971-19-39
East Midlands Regional Exam Board	1974-26-18
East Rudham	1972-22-44
East Runton	1974-27-8/10 1979-31-49
East Winch	1978-30-10/113
East Wretham Heath	1971-19-39/40
Easton	1954-2-4
Easton Bavents	1953-1-6 1955-4-1...4 1972-22-11...31 1974-27-44 1977-29-26 1982-32-55 1983-33-41
Eaton	1968-16-17/19 1969-18-8/11 1973-24-3...14 1983-33-27/32
Eau Brink Cut	1976-28-35/37
Echinocorys	1957-6-1 1968-16-17 1971-20-27 1973-24-8
Echinus	1977-29-27 1978-30-87/113 1979-31-76 1983-33-29 1985-35-36/40
Edmonds, E.A.	1974-25-25/32/34 1983-33-64
Edmunds, F.H.	1974-27-11
Edwards, D.	1979-31-16
Edwards, E.	1974-25-10
Eemian interglacial	1972-21-8 1973-23-7 1978-30-88
Egglestone, J.F.	1974-26-27/28
Eiriksson, J.	1977-29-44/59
Elbow deposits	1972-21-8
Elder	1973-24-9
Elegans zone	1979-31-64
Elephant	1957-6-1 1969-18-18 1972-22-5 1978-30-29/87
Elkton Rift	1974-27-56
Ellingham	1974-27-7/9/10
Ellis, E.A.	1979-31-35
Ellobium	1974-27-29 1983-33-42
Elofsonella	1978-30-114/116 117
Elphidiella	1979-31-1/2/7 1982-32-41/57

Elphidiella (cont) 1983-33-55...57 60/62 1984-34-88/89

Elphidium 1978-30-118 1979-31-1/2/4/7 8/9/13 1983-33-40/48/55 ...57/60/62 1984-34-85

Elster-Saale 1956-5-6 1957-7-2

Elsterian 1972-21-8 1973-23-7

Elsworth 1985-35-17

Ely 1974-25-21...38 1978-30-14/15 1985-35-19

Elytra of beetles 1972-22-4

Emarginula 1978-30-96

Embankments 1976-28-29

Embryo-dune 1977-29-52

Emmian interglacial 1956-5-6

Emys lutaria 1972-22-4

Emys orbicularis 1985-35-65

Ena montana 1969-17-7

Endecott machine 1972-22-20

Endemoceras 1984-34-31

Engine drain 1979-31-65

Englefield, H. 1979-31-67

English Channel 1972-21-2/3/6

Ensis complanatus 1978-30-110 1979-31-75

Entodon concinnus 1983-33-63/67

Entolium 1974-27-30

Eocene 1972-21-2 1977-29-35 1978-30-40/97

Eonavicula 1985-35-15/17

Epidote 1957-7-4

Eponides 1983-33-40/43

Equus caballus 1972-22-8

Erdman, D.A. 1971-20-15

Eremophila alpestris 1985-35-64

Ericales pollen 1972-21-21 1972-22-15

Eriswell 1974-25-26

Erklenz axis 1956-5-1

Erosion 1968-16-2/3 1972-21-29...40

Erratics 1971-19-33 1972-21-28 1973-23-6/7 1974-27-63/64 1977-29-40 1978-30-5/14/19 22/24 1979-31-18

Esker 1978-30-18/30 1979-31-22

Essex 1974-25-23 1974-27-38 1976-28-53

Euncytheridea Bradii 1978-30-116

Eudexus 1979-31-54/55/5

Euhoplites 1969-17-9

Evans, C.D.R. 1978-30-8/36/38 1979-31-19/21/2 28

Evans, G. 1971-20-38

Evans, H. 1971-20-17...25
1972-21-11/15
1973-23=11...24
1975-27-61...75
1978-30-118

Evans, P. 1971-20-38

Exochella eleanorae 1985-35-45

Facines 1976-28-31

Faecal pellets 1979-31-55/63

Fairbridge, R.W. 1971-20-15

Fairstead & Middleton Towers Station 1978-30-10
1979-31-60

Fakenham 1976-28-31

Falun du Luchtbal 1977-29-30

Faujasina subrotunda 1983-33-52/60

Faults 1974-27-16

Fearnsides, W.G. 1985-35-6/13

Felbrigg 1976-28-12

Felixstowe 1977-29-56

Feltwell Fen 1974-25-28/31

Fennel 1973-24-9

Fens 1971-19-6/30
1974-25-21/26/28
1976-28-30/33
1978-20-23/30..
32/36
1979-31-20/21
46/60

Ferruginous concretions 1971-19-32
1974-27-22/61/63
1977-29-28/29

Ficula condita 1977-29-33

Field relations 1973-23-36

Field mapping 1974-26-4

Fieldwork in geology 1972-22-36
1974-25-17
1974-26-3...46

Filicales 1972-22-15

Filipesco, M.G. 1967-15-5

Fish 1972-21-43
1974-27-41/44
1978-30-83/87
1979-31-56/71/76

Fisher, M.J. 1972-21-8/9

Fisher, R.A. 1974-27-69/74

Fishley Carr 1976-28-46

Fissurina 1983-33-60

Fitch, R. 1974-25-8/11
1984-34-69

Fitton, W.H. 1979-31-65/67
1985-35-9/10/13

Flakes 1978-30-85

Flaser Beds 1977-29-27/28

Flandrian 1974-25-38
1976-28-49/55
1979-31-13/24
1984-34-92

Fleischer, U. 1971-20-15

Flint, R.F. 1974-27-65/74

Flint & pebbles 1957-6-1
1959-9-1...4
1968-16-17/19
1969-18-17
1971-19-35/36
1972-21-25/42
1973-23-11/30
1973-24-28/37
1974-25-23
1974-27-34/36..38
41/61
1977-29-27/29/40

Flints & pebbles (cont) 1978-30-23/31/55 58/67/83/89/92 93/95/97
1979-31-18/21
1982-32-20/55

Flint erratics 1971-19-35/36
1978-30-8

Flood plains 1971-19-27

Flordon 1977-29-36
1982-32-51...59

Florida 1977-29-38

Flotation 1979-31-1

Flower, J.W. 1974-25-26/34

Floyd, R. 1978-30-38

Flustra eoliacea 1969-17-12
1972-22-44
1977-29-40

Fluvial 1972-21-81
1978-30-61/64/68 70/93

Fluvio-marine 1977-29-38
1979-31-72

Foam impressions 1977-29-52

Fodder Fen Common 1974-25-24

Foddestsone Gap 1979-31-58

Foliation 1962-11-7

Folkes, M. 1974-25-5

Folkestone 1967-15-3
1983-33-3

Foraminifera 1955-3-5
1959-9-2
1972-21-2/7/26 26
1972-22-21
1974-25-32
1974-27-33/37/40
1978-30-64/93/97 113
1979-31-1/8/15/71

Foraminfera (cont) 1983-33-6/35..62
1984-34-85/88/89
1985-35-47...51

Forbes, C.L. 1974-25-21
1983-33-63
1985-35-5/6/13 32

Forbes, L.W. 1979-31-48/63/ 64/67

Ford, T.D. 1974-27-18

Fordham 1978-30-11
1979-31-58/61/62

Forest bed 1971-20-29..31
1972-21-17

Forestry Commission & Nature Conservancy 1971-19-2

Forsdike, R. 1971-20-27

Fort Worth 1969-17-13

Fossil wood 1972-21-42

Fossil soil horizon 1977-29-20

Foston 1974-27-5

Foulger, W. 1974-25-10

Foulsham 1976-28-21

Foundation Course 1983-33-35

Four Ashes 1974-27-7/9...1

Fowler, A.K. 1968-16-17...21
1969-18-4/5

Fowler, G. 1974-25-27/31/3

Fox, M. 1974-25-10

Foxhall, Ipswich 1978-30-88

Fracture 1978-30-39...54

Fragaria 1971-20-34

Francis, E.A. 1966-14-1

Fraxinus excelsior 1983-33-67

Freckenham Series 1973-24-43

France 1977-29-4

Freeze-thaw 1973-23-13

Freiastarte 1974-27-30

Freshwater shells 1972-21-43
1977-29-20

Frettenham 1969-18-11

Friedman, G.H. 1978-30-61/75

Friend, P.F. 1969-17-9
1984-34-124

Frost structures 1973-23-3/16
1978-30-31/34/36
1979-31-31

Fulica atra 1985-35-63

Funnell, A.M. 1982-32-39...50
1983-33-43/44

Funnell, B.M. 1954-2-2...5
1956-5-1...5
1957-6-1...4
1957-7-1...3
1961-10-10
1965-13-7
1968-16-18
1969-17-3
1971-19-42
1971-20-2...16
1972-21-2...10
15/21/30
1972-22-21
1973-24-37...44
1975-27-33/36/40
1977-29-1
1978-30-103/113
118/119
1979-31-1...16/
31/33/35...44
69/70/72...74
1982-32-1/4/20
29/30/39///50
53/59
1983-33-35...62

Funnell, B.M. (cont) 1984-34-78...88
123...140

Fürsich, F.G. 1985-35-14/15

Fysh, M.D. 1984-34-106

Gadoid otoliths 1974-27-44
1978-30-87

Gadus morrhua 1974-27-44

Galena 1974-27-8

Galeola 1973-24-8

Galerida 1985-35-65

Galerites 1973-24-18

Gallinula chloropus 1985-35-60

Gallois, R.W. 1973-23-25...34
1975-27-21/27
29...31
1978-30-3...38
119
1979-31-17/18/22
24/28/45..67/70
1984-34-3..64/107
1985-35-6/10/20

Gallus 1985-35-61

Gammon, K.M. 1982-31-2

Gardner, K. 1975-27-47...53
1977-29-44
1979-31-34

Garnet 1957-7-4
1974-25-33

Garrels, R.M. 1982-32-63/67

Garrulus glandarius 1985-35-60

Gas 1974-27-5

Gaskell, T.F. 1971-20-13

Gas pipeline 1978-30-16/23
1979-31-71

Gaster, C.T.A. 1971-20-26/28

Gastrana 1978-30-100

Gastrochaenolites 1985-35-15

Gastrochaenopsis 1985-35-14/26

Gastropods 1971-20-21
1972-21-2
1972-22-24
1973-23-29
1974-27-25/29/39
1978-30-87
1979-31-55
1985-35-36

Gater, J. 1979-31-16

Gault 1957-7-4/5
1969-17-7...9/13
1974-25-23/29
1978-30-14
1983-33-3...26
1985-35-20/22/23

Gavelinella 1983-33-7/11/13
26

Gayton 1979-31-49
1983-33-24

Gaywood 1978-30-23
1979-31-48

Gaywood Bridge 1978-30-10

Gaywood River 1978-30-8

Gedgravian 1978-30-96
1979-31-24/25
1984-34-75/82
1985-35-47

Geiger, M.E. 1971-20-15

Geikie, A. 1974-26-4

Gemstones 1974-25-3

General Certificate of Education 1972-22-33...42
1974-26-8/32/38
39

Geochemistry 1973-23-48

Geodes 1969-18-4/5
1971-19-32
1979-29-32/33

Geological Society of Norfolk 1979-31-1/72/73

Geological Society, Quaternary Era Sub-Committee 1978-30-4

Geological Survey Map 1976-28-49...67
1979-31-19
1984-34-85

Geomorphology 1984-34-86

Geophysical Surveys 1974-27-3/17

Geophysics 1973-23-48

George, T.N. 1971-20-37
1974-26-6

Georges Bank, Massachusetts 1977-29-56

Geosynclinal 1967-15-4
1971-20-22
1974-27-9

Germany 1962-11-9
1971-20-6
1974-25-6
1974-29-31
1977-29-42
1978-30-117
1985-35-71

Gervillia 1957-6-1
1985-35-14/17

Gibbula tumida 1957-7-1
1972-22-16/22
1979-31-76

Gill, W.D. 1971-20-15

Gillet, S. 1974-27-30/31

Gimingham 1972-21-42
1974-27-56...58

Gipping outwash gravels
1961-10-9
1966-14-3
1972-22-5
1973-23-5/6
1974-27-69
1979-19-33

Gipping till
1956-5-6
1957-7-2
1971-19-33

Gipping Valley 1971-20-26...28

Girling, M. 1979-31-28

Glacial deposits, bibliography of 1963-12-4...7

Glacially filled valley
1957-7-2
1978-30-12/40

Glacial stratigraphy 1956-5-6/7

Glacial tectonics 1962-11-1...17

Glacio-fluvial deposits
1963-12-1...4
1968-16-1...16
1971-19-35
1971-20-36
1973-23-5
1974-27-55
1978-30-39
1979-31-20/22/71

Glandford 1968-16-5

Glauconite
1973-24-5
1974-25-23
1977-29-29
1984-34-25

Glaren, R. 1976-28-6

Glen, J.W. 1962-11-8

Gleying
1971-19-4/7
1976-28-6

Glinton 1974-27-5/11

Globigerina
1959-9-1
1983-33-20/48

Globulina 1983-33-57/60

Glomar Challenger 1977-29-59

Glycymeris
1971-20-35
1977-29-33
1978-30-98
1982-32-37

Gneissic rocks 1978-30-19

Godwin, H. & M.E.
1974-25-27/28
32/34
1979-31-16

Goff, J.C. 1973-24-3...14

Goldsmith, J.G. 1973-24-3...14

Golterman, H.L. 1982-32-62

Goniomya 1985-35-14

Gonioteuthis 1971-20-26/27

Gorleston
1972-21-29...35
1976-28-64

Gramineae
1972-21-21
1972-22-15

Grand Banks, Newfoundland 1977-29-56

Grantham 1979-31-19

Granulometric analysis 1978-30-102

Graptolites 1971-20-21

Gravel
1957-6-1
1966-14-1/3/4
1968-16-17/19
1969-17-3...5
1969-18-13/14
16/17
1971-19-9/17/21
4/30/33/35/37/41/42
1971-20-32/34
1972-21-25
1972-22-25
1973-23-6-15/17
18/22
1973-24-37/43
1974-25-24/38

Gravel (cont)	1978-30-18/22.. 24/31..33/55/64/68/68 70/72/79/81/83/85/89/95 1979-31-4/24/26 31/64 1982-32-20/51..59 1984-34-125-128 133/135
Gravenor	1974-27-66/74
Gravesia	1979-31-56/66
Gravity and magnetic anomalies	1974-27-3/10/14 15 1978-30-105/112
Great Blakenham, Suffolk	1977-29-11
Great Fen	1974-25-23
Great Hockham	1971-19-39
Great Massingham	1978-30-8/39
Great Paxton	1974-27-4
Great Pit, Whitlingham	1979-31-71
Green, C.	1979-31-36/41/44
Greenly, E.	1974-26-4
Greensand	1957-7-5 1967-15-2 1969-18-4/5 1974-25-22/23 1974-27-4/27 1978-30-14
Gregoryceras	1985-35-11
Greensmith, J.T.	1974-26-5
Grendelius mordax	1979-31-62
Grenville-Cole	1974-26-4
Gresham House	1973-24-43 1974-25-4
Gresham's School	1972-22-33
Grew	1974-25-4
Greywacke	1967-15-4
Grimes Graves	1978-30-47/48
Grinston	1978-30-10
Gronlung, N.E.	1974-26-27/45
Grundisburgh	1978-30-92
Grunty Fen	1974-25-21/22/24
Grus	1985-35-63
Guist	1974-27-13 1982-32-52...59
Gunn, R.J.	1974-25-9/11 1978-30-55/57
Gunton	1978-30-74
Gurney, H.	1974-25-6
Gurney, A.	1974-25-10
Guttulina	1979-31-2 1983-33-40/60
Gypsum	1971-20-9 1976-28-35 1979-31-55/57
Gyrohelix	1977-29-35
Haanstra, U.	1971-20-15
Haddenham End Field	1974-25-21
Hadleigh	1978-30-97
Hagenowia rostrata	1957-7-6
Hails, J.R.	1971-20-38
Hainton	1979-31-21
Haliaeetus	1985-35-64
Halimione portulacoides	1984-34-129
Hall Series	1973-24-43

Hallam, A. 1983-33-14

Hallam, S.J. 1974-25-45

Halokinesis 1971-20-8/9/11

Hamites 1969-17-9
1973-23-26/30

Hampshire Basin 1972-21-2

Hancock, J.M. 1962-11-12
1965-13-7
1967-15-1...6
1968-16-11/17
1969-18-6
1971-20-26/28
1973-24-5
1974-25-23
1974-27-57
1982-32-62
1983-33-27/32
1985-35-71

Hansen, S. 1974-27-56/59

Hanslope Series 1971-19-20/21
24/30

Happisburgh 1968-16-2
1972-21-21/34/35
1974-27-58
1976-28-21/59/66
1984-34-110

Hardgrounds 1973-24-5...7

Harding's Drain 1974-25-24

Hardwick 1978-30-23

Hardy, M.A. 1984-34-124

Harmer, F.W. 1975-27-34/43
1977-29-23/34/36
37/41...43/56
1978-30-79/80/90
1979-31-9/30/72
77
1984-34-6/7/75
85

Harpum, J. 1974-26-4

Harrimere 1974-25-31

Harrison, C.J.O. 1985-35-53...69

Harrison, P.W. 1961-10-12
1962-11-11

Harrod, T.R. 1979-31-19/28

Hart, J. 1984-34-103...122

Hart, M.B. 1983-33-3/7/20

Hartshorn, J.H. 1974-27-74

Harwick 1974-27-4/9

Hascott Hill 1977-29-26/43

Haslam, E.S.M. 1983-33-64

Hatch, F.H. 1959-9-3

Haugh Lane, Woodbridge 1978-30-93

Hauterivian 1974-27-31

Hawthorn 1973-24-9

Heacham 1973-23-32
1978-30-18
1984-34-11/22/27

Heather 1971-19-41

Hectoroceras 1984-34-20/21

Hedbergella 1983-33-7/11/13
20/26

Helhoughton 1978-30-50/53

Helicigona lapicida 1977-29-41

Hemiaster 1969-17-9

Hemithyris psittacea 1974-27-39/41
1979-31-76

Hempstead 1976-28-6/8/14

Henham 1977-29-26

Henley, H.H. 1974-25-10

Hessle till 1978-30-29

Hestbrepiggan 1961-10-5/8/9

Hevingham 1977-29-9

Hexanchus 1978-30-87

Hey, R.W. 1972-21-22
1978-30-93/103
1979-31-31/34
1982-31-1
1982-32-51/59
1984-34-91/115
1985-35-6/20

Heybrock, R. 1971-20-15

Hiatella 1971-20-35
1972-22-15/17/19
23/26
1978-30-86
1979-31-4/6/8/75
1985-35-14

Hieratus 1985-35-65

High level gravels 1974-25-38

High Lodge Site, Mildenhall 1971-19-41

Highway Engineer 1976-28-29...48

Hilgay 1978-30-15/32
1979-31-48/49

Hill, W. 1959-9-2/4
1974-25-23/25
1983-33-6

Hillington 1974-27-61
1978-30-10

Himus, G.W. 1974-26-4

Hinde, P. 1971-20-15

Hingham 1978-30-40

Hinz, K. 1971-20-13

Hippopotamus amphibius 1969-18-18
1972-22-4/8
1977-29-41
1978-30-29/88

Hirschmannia 1978-30-116

Histon Road deposits 1957-7-2

Hoary Mullein 1973-24-9

Hochland 1974-25-32

Hockering 1954-2-4

Hockwold Fen 1974-25-26/27

Hodge, C.A.H. 1974-25-21/35
1976-28-3...27
1977-29-3

Hodgeson, J.M. 1976-28-16/26

Holaster 1969-17-7/9
1982-32-62

Holderness Peninsula 1972-21-37
1973-24-16
1978-30-29
1979-31-25

Holectypus 1985-35-14/25

Hole Farm, Plumstead 1977-29-3...11

Holkham 1976-28-57
1977-29-36...55
1984-34-131

Holland 1956-5-2
1967-15-5
1973-24-29
1974-27-55
1976-28-20
1977-29-4
1984-34-77

Hollesley 1977-29-57

Hollin, J.T. 1962-11-7

Holme 1984-34-123/131

Holmes, C.D. 1962-11-10/11
1973-23-6/8
1974-27-66/74

Holocene 1977-29-24
1982-32-20

Holocene deposits 1956-5-3
1967-15-6
1977-29-25/31
1978-30-23/32
36/119
1979-31-11...16
40/43
1982-32-14/20
1984-34-123..140

Holsteinian 1956-5-6
1972-21-8
1973-23-7
1978-30-117

Holt 1973-23-7
1976-28-4/12/20
1977-29-3/7
1984-34-113

Holton 1971-19-33

Holway Road 1973-24-44

Home kit 1973-23-36

Honeyhill 1974-25-24

Honingham 1954-2-5

Hooke, R. 1974-25-4

Hooper, J.M.D. 1973-24-14

Hoppe, G. 1974-27-66/74

Horberg, L. 1962-11-9

Horizons 1971-19-4/9/20

Hornabrook, J.T. 1971-20-15

Hornby, R.J. 1973-24-3...14

Horne, D.J. 1983-33-54

Horning 1971-19-2/31

Horse 1971-20-19...31
1972-22-5/8

Horse Fen 1978-30-17

Horton 1978-30-12/33/36

Horton, A. 1984-34-116

Hoskisson 1973-24-17

Howard's Hill, Cromer 1971-19-35

Howarth, H.H. 1962-11-12

Howe 1978-30-117

Howlett, D.R. 1955-3-5

Hoxne 1956-5-6
1957-7-2
1968-16-9
1969-18-13...16
1972-21-26
1983-33-45

Hoxnian 1961-10-9
1968-16-19
1973-23-3/4/6/7
1978-30-113
1979-31-23/25/26

Hudleston, W.H. 1985-35-9/10/12

Hudlestoni 1979-31-54/55

Hudson, J.D. 1967-15-2

Hughes, T.M. 1985-35-3

Human remains 1978-30-88

Humus 1971-19-4

Hundred Level Drains 1976-28-33

Hunstanton Raised Beach 1957-7-5
1972-22-2/43
1974-26-47...48
1974-27-21/30
1977-29-46
1978-30-3/23/30
31/33/34
1979-31-25/25/49

Hunstanton Gasworks 1978-30-22

Hunstanton till 1956-5-6
1968-16-8
1972-22-2
1973-23-3
1973-24-25...34

Hunstanton till (cont)	1975-27-21...27 1977-29-4 1978-30-3/18/19 29...33/36 1979-31-22/23/ 26/27
Hunstanton Escarpment	1978-30-13
Huntingdon	1974-25-27 1974-27-4 1978-30-12
Hutchinson, J.N.	1979-31-36/41/44
Hutton, J.	1958-8-1/2 1974-25-6/11
Hybrid Medick	1973-24-9
Hydraulics Research Station	1972-21-29/33
Hydrobia	1972-22-29 1977-29-28 1979-31-7/11
Hydroid	1985-35-37
Hydrogen peroxide	1977-29-7
Hyperosteosis	1974-27-44
Hypersaline	1971-20-5
Hystoceras	1983-33-11...13
Hythe Beds	1973-23-26
Ice	1961-10-3/6 1962-11-2/4...6 1966-14-2 1968-16-11 1969-17-8
Ice, bibliography of	1963-12-4...7
Ice dammed lakes	1978-30-16
Ice wedge casts	1961-10-7 1968-16-6 1975-27-47...53 1977-29-40 1978-30-61/72 1979-31-33
Iceland	1971-20-13 1977-29-40/41
Icenian	1956-5-3 1957-7-3...5 1974-27-34/36.. 38/41/43 1977-29-37 1978-30-77/79.. 81/83/84
Ichthyosaur	1979-31-61/62/ 67
Ightham fissure	1985-35-64
Igneous rocks	1971-20-20 1973-24-37 1978-30-19
Ilex	1957-7-2
Illite	1979-31-51
Impregnated fossil wood	1971-19-33
Inclinometers	1976-28-37/45
Indo-Pacific	1974-27-44
Infulaster	1957-7-6
Ingle-Smith, D.	1973-23-16/23
Ingoldisthorpe	1957-7-5
Inner Silver Pit	1972-21-8
Inoceramus	1953-1-7 1957-7-5 1969-17-7/9 1974-25-10 1974-26-47 1978-30-95
Institute of Geological Sciences	1974-27-18/29 1976-28-8 1978-30-37/54/ 105
Interference ripples	1977-29-52
Interglacials	1957-7-2 1969-18-17...19

Interglacials (cont) 1972-22-2...9
1977-29-42

International gravity formula 1978-30-109

Intra basement magnetisation 1974-27-12

Intraformational Breccia 1977-29-29

Intrusion 1974-27-14

Involutions 1973-23-11...24

Ipswich 1984-34-92

Ipswich Geological Group 1972-22-12
1979-31-1

Ipswich Museum 1977-29-38
1978-30-78

Ipswichian interglacial 1956-5-6
1968-16-8
1971-19-14
1972-22-2/4...6
1973-23-5/6
1974-25-24/38
1977-29-44
1979-31-15...16
23/25/26
1983-33-63/64
70/74
1984-34-92/111
1985-35-63

Iron 1969-18-4/5
1971-19-4/32..34
1972-21-42
1972-22-43
1974-27-24/34
1978-30-22

Isastraea 1985-35-14

Isle of Sheppey 1972-21-2

Isleham Fen 1974-25-28

Isoarca 1985-35-17

Isocardia cor 1984-34-77

Isocrassina 1978-30-100

Isostatic 1978-3-8

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Jackson, J.F. 1984-34-30

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Jarosite 1974-25-21/22
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Jasper 1978-30-22
1979-31-76

Jeans, C.V. 1983-33-21/25
1984-34-42/50

Jeletsky, J.A. 1955-3-5
1957-6-2

Jenkyns, H.C. 1983-33-16

Jennings, J. 1974-25-27/35
1979-31-35/44

Joby, R.S. 1971-20-32/33
1972-22-39...42
1977-29-1

Joint Matriculation Board 1974-26-10/28

Joist Fen 1974-25-23/28

Jones, T.R. 1978-30-113/114
118
1984-34-69/85

Jones, O.T. 1971-19-42

Joysey, K. 1972-22-4

Judy hard peat 1979-31-13

Jukes-Browne, A.J. 1959-9-2/4
1962-11-12
1971-20-26/28
1973-23-26/32/34

Jukes-Browne, A.J. (cont) 1974-25-10/12
23/35
1974-27-19
1978-30-22/29
37/88
1984-34-6/27/31
1985-35-6

Jurassic (limestone) 1957-7-3
1969-17-11/13/14
1971-19-33
1971-20-8...11
1974-25-21/22/29
1974-27-63
1978-30-58/64
67/74
1979-31-17/19
20/45
1982-32-55
1983-33-16
1984-34-3...64
1985-35-3...38

Kallo 1977-29-25/30/34

Kamb, W. 1962-11-9

Kaolinite 1979-31-51

Kaye, G.W.L. 1961-20-2

Kaye, P. & Barker, D. 1974-27-31

Karstik 1972-21-6

Kattendijkian 1977-29-25/30/33

Kazi, A. 1974-27-58/59

Keeping, W. 1973-23-25/30
1974-27-24/27
1985-35-18/20/23

Kellaway, G.A. 1961-10-11
1962-11-10

Kelling 1976-28-6

Kelly, S.R.A. 1984-34-14/20/56
1985-35-3...38

Kennard, A.S. 1983-33-69

Kennedy, W.J. 1971-20-37
1983-33-17

Kennet 1969-17-8

Kennyhill 1974-25-26

Kent, R.E. 1971-20-2/7/10
12/15
1974-27-3/9/13
1979-31-68
1984-34-14
1985-35-16

Kerney, M. 1977-29-45
1983-33-69

Kerr, J. 1974-26-27/29

Kerogen 1979-31-46/50/5

Kesgrave formation 1982-32-53
1984-34-90/91

Kesteven 1979-31-19/20

Keswick 1969-18-11

Ketton Quarry 1967-15-2

Keunen, P.H. 1973-23-22/24

Keuper marl 1967-15-2/3
1971-20-3/9
1974-27-4
1979-31-24

Kidderminster 1965-13-6

Kidney vetch 1973-24-9

Kidson, C. 1973-24-16/28/3

Kildewijn, B.W. 1967-15-5

Kilns 1973-23-4/37

Kimmeridge Clay 1973-23-35
1974-25-21/22
28/38
1974-27-63
1976-28-33/35
1979-31-45...70

King, J. 1974-25-11/12

King, W.B.R. 1985-35-9

Kingena 1973-24-7

Kingenella	1985-35-41/42/43
Kingery, W.D.	1962-11-8
King's Lynn	1974-27-13 1976-28-33...38 1978-30-11/23 1979-31-46/50 60/69
Kippett Hills	1982-32-37/38
Kirby	1973-24-17
Kirkaldy, J.	1972-22-41 1984-34-11
Kirkby on Bain	1979-31-21
Kitton, F.	1974-25-4/5/12
Knapton	1971-20-32/33
Knills, J.L.	1974-27-58/59
Knopf, A.	1967-15-4
Koldijk, W.S.	1978-30-57/61/75
Kottlowski, F.E.	1974-26-4
Knowles, L.	1972-22-41
Kruisschans	1977-29-25/31/35
Krumbein, W.C.	1974-27-74
Ksiazkiewicz, M.	1967-15-5
Kupsch, W.U.	1974-27-56/59
Kyanite	1957-7-4 1974-25-23
La Hague Trough	1972-21-4
Laby, T.H.	1961-10-3
Lacuna	1978-30-120
Lackford	1971-19-42
Laevaptychus	1979-31-52/55/65
Laevicardium	1971-20-35 1977-29-33
Laga, P.	1984-34-77
Lagaaij, R.	1984-34-77
Lagena	1983-33-60/62
Lagoons	1965-15-6 1973-24-17/25/30
Lahee, F.H.	1974-26-4
Laird, W.M.	1969-17-8
Lake, R.D.	1984-34-91
Lakenheath	1974-27-7/9..11 1978-30-15 1979-31-49
Lambert, C.A.	1974-25-25/35
Lambert, J.M.	1979-31-35
Lamboy, M.	1972-21-6
Lamellibranchs	1955-3-5 1971-20-21 1974-27-36 1978-30-113
Laminae	1971-19-36
Lamplugh, G.W.	1973-23-26/30/34 1978-30-29/37 1984-34-34
Lancashire	1979-31-35
Landguard Point	1973-24-16
Lang, W.D.	1983-33-27
Langham	1978-30-97
Langmere	1971-19-40
Langwood Hill	1974-25-24
Lankester, R.	1978-30-88...90
Lark River	1971-19-42 1974-25-28/31 1978-30-11/15/31
La Rochelle	1985-35-18

Larwood, G.P. 1953-1-5/7
1955-3-5
1969-17-10...15
1972-22-21
1983-33-27
1984-34-11/42

Lasaea 1972-22-17

Lavenham 1978-30-102

Lawrance, P. 1977-29-56
1978-30-119

Layton, J. 1974-25-7/11

Leathes, G.R. 1974-25-10

Le Bas, M.J. 1974-27-3/4

Leda myalis 1965-13-1
1972-21-17

Leeder, M.R. 1968-16-17...21
1969-18-6...12
1971-20-26
1973-24-5/14
1977-29-59

Lees, B.J. 1982-32-1...35
1984-34-75

Lees, G.M. 1967-15-4

Leicester, P. 1971-20-16

Leicestershire 1974-27-5/11

Leigh, A. 1972-22-4

Leigh, R. 1974-26-45

Lenham 1956-5-1/2
1977-29-25/32
33/42

Lenticulina 1979-31-2
1983-33-40/60

Lentidium complanatum 1977-29-35

Leonardo da Vinci 1974-25-3

Leopold, L.B. 1973-24-23/33
1978-30-70/75

Leptocythere castanea 1978-30-114

Lepton nitidum 1972-22-15/16
19-23

Le Strange, H. 1973-23-26/30/3
1974-26-47/48
1974-27-21/27
1975-27-27
1984-34-50

Lesser Redmere 1974-25-30

Lessig, H.D. 1974-27-56/59

Lessivage 1971-19-4/9

Lewesiceras 1969-17-9

Lewis, W.V. 1971-19-42

Lexham 1978-30-11

Lexique stratigraphique 1978-30-80/90

Leziate 1973-23-31
1975-27-26
1978-30-14
1984-34-12/21..

Lias 1967-15-2
1971-20-3

Liassic 1971-20-9
1974-27-4/5

Lightwing, J.L. 1983-33-73...80

Lima 1971-20-35

Limatula cf. tombeckiana 1974-27-30

Lime Kiln Hole 1978-30-77
1985-35-71/72

Limestone 1959-9-2
1969-17-13
1973-24-37
1974-29-9
1979-31-18
1985-35-21/25

INDEX (1953-85)

Limonitic material
1971-19-33
1973-23-13/29
1974-27-22/24

Lincolnshire
1971-20-11
1974-27-3/21
1976-28-57
1978-30-15/29
1979-31-17/18
20...24/24/26

Lincolnshire limestone
1967-15-2
1971-19-33
1971-20-10
1978-30-8

Lingula
1979-31-57/60

Linsser, H.
1974-27-15/17/18

Linton, P.L.
1956-5-2

Liostrea
1985-35-15

Litcham
1978-30-10

Lithophaga
1985-35-14

Little Chishill
1974-27-7/9/11

Little Downham
1974-25-26

Little Hautbois
1961-10-9

Little London
1974-25-22

Little Marl Point
1972-21-42

Little Ouse
1974-25-23/27
1978-30-11

Littleport
1974-25-31
1978-30-11/15

Littoral
1972-22-27
1977-29-31
1978-30-95/96

Littorina
1969-17-6
1971-20-4
1972-21-43
1972-22-16/22
24/26
1974-27-36/37
39/40/42/43
1977-29-38/40

Littorina (cont)
1978-30-84/87
1979-31-4/6..8/11
72/75/76
1983-33-41

Liversidge, J.
1974-25-31/34

Llanvirnian
1974-27-4

Llibouty, L.
1962-11-9

Loam
1972-22-13
1973-24-37/41
1976-28-3/8
1977-29-3
1978-30-83
1979-31-19/31

Loddon
1976-28-28...41
1977-29-9

Lodge Farm, Hunstanton
1973-23-27/30

Loess
1976-28-16/17
1977-29-3...22

London Basin
1972-21-2
1985-35-63/64

London Exam Board
1974-26-12

London-Brabant Massif
1974-27-3/17

London Clay
1969-17-4
1971-19-32
1971-20-36
1972-21-2
1973-24-19
1977-29-27/35
36/40
1979-31-32
1984-34-75

London Platform
1979-31-45/50

Long Sutton
1978-30-11

Lopha
1985-35-17

Lora sp.
1972-22-16
1978-30-87
1979-31-26/29

Lord, A.R. 1969-17-3...5
1969-18-13...16
1972-21-6/7/9
25...28
1978-30-103
113...118
1983-33-45
1984-34-80

Lordsbridge 1978-30-11

Lothingland, R.D.C. 1972-21-31

Lower Carboniferous 1971-20-21

Lower Cretaceous erratics 1978-30-8

Lower Cretaceous sandstone & ironstone 1978-30-5/58/64

Lower freshwater bed 1972-21-43

Lower Greensand 1973-23-25/26
1974-25-22/23
26/38
1974-27-5/21
1978-30-14

Lower Tottenhill gravel 1978-30-3

Lowestoft 1956-5-3/6
1957-7-2
1961-10-9
1965-13-2
1966-14-3
1968-16-8
1972-21-17/26
31/34
1973-23-3
1973-24-37
1974-27-5/3/9
15/58
1977-29-7
1978-30-55/61/64
66/67/70/72/113
1979-31-17/23/24
33/41/49

Luchtbal 1977-29-25/30

Lucina miniscula 1979-31-57/60/63

Lucinoma 1972-22-16/23

Ludham 1969-17-3
1972-21-7/18...2
41
1972-22-11/12/15
28/29
1982-32-42
1984-34-85

Ludhamian 1972-21-20
1972-22-12
1982-32-45/48
1983=33-45..49/4

Lutraria 1978-30-98

Lyell, C. 1958-8-1/2
1965-13-1
1974-25-6/9/12
1975-27-20/28/54
1979-31-78
1984-34-69/75

Lymnaea 1975-27-39

Lynnia 1984-34-21

Maastrichtian 1972-21-42
1972-22-44
1983-33-32
1985-35-41/43

Maclintock, P. 1974-27-71/74

Macfadyen 1974-25-32

Mackenzie, F.T. 1982-32-63

Macoma 1971-20-35
1972-21-2/41/42
1972-22-17/19/2
23/24/26/27
1974-27-36/41
1977-29-38...40
1978-30-77/79
80...91/96/100
1979-31-4/6/8/9
75
1982-32-37/41
53/57
1983-33-41/42

Macrofossils 1979-31-11

Macro-gelivation 1973-23-13

INDEX (1953-85)

Mactra corallina 1978-30-86

Madgett, P.A. 1977-29-21
1979-31-25
1984-34-113

Magas pumilis 1957-6-1

Magnetic anomalies 1974-27-11/13
14/15/17
1978-30-105

Magnetization 1974-27-13

Malta 1978-30-119

Mammaliferous Clay 1977-29-39

Mammals 1972-22-2...9
1974-27-39

Mammoth 1972-22-5/8
1974-25-3
1983-33-77

Manea 1974-25-21

Mangelia 1971-20-35

Mantell, G.A. 1974-25-10

Marcasite 1971-19-32
1974-27-8

March 1957-7-1
1972-21-8
1974-25-24/29
31/28
1978-30-11/30..
33/36

Marham 1978-30-47/48
1979-31-49
1983-33-24

Marine transgression 1974-27-9/39
1984-34-123

Market Weighton, Humberside 1979-31-45

Markfieldite 1971-20-32

Markham, R.A.D. 1965-13-4..7/95
1969-18-17..19

Markham, R.A.D. (cont) 1971-20-26...31
1972-22-4
1977-29-38
1978-30-104
1979-31-73
1982-32-12

Marlingford 1954-2-4

Marl pits 1972-22-44

Marly drift 1971-19-35/36
1973-23-6/7
1973-24-41
1974-25-27/31/38
1976-28-3/8
1979-31-21/22/24
1984-34-103

Marr, J.E. 1978-30-31

Marsham 1977-29-9

Marsupites 1971-20-26

Martello Tower 1973-24-19

Martin, A.J. 1953-1-6
1956-6-6/7
1958-8-1/2
1972-22-21
1985-35-5

Mason's Pit, Great Blakenham 1971-20-26

Mathers, S.J. 1984-34-65..101

Matthews, W.H. 1974-27-56/59

Matlask 1971-19-24

Mattishall 1977-29-5

Maynard, J.E. 1959-9-3
1969-18-5

Maxwell, J.A. 1982-32-62

McArthur 1973-23-42/44/45

McCave, I.N. 1976-28-53/67
1977-29-59
1984-34-18/14/125

McKay, J.R. 1974-27-56

McGowan, C. 1979-31-68

McLachlan, A. 1985-35-25

McWilliams, B. 1972-22-2...9
1974-25-3...14
1978-30-119

Meandropora 1969-17-11

Medawar, P.B. 1974-26-36

Mediterranean 1978-30-88

Megaceros giganteus 1969-18-18
1972-22-4

Melampus 1978-30-87

Meltwater 1978-30-70
1979-31-22

Membranipora 1969-17-13

Mepal 1974-25-25

Mercenaria 1982-32-46

Meres 1971-19-40

Mergus serrator 1985-35-59

Merksemian 1977-29-25/31
35/38

Merlerault axis 1957-7-3

Merton 1971-19-39

Mesolithic (flint tools) 1972-22-2/8
1974-25-28

Mesozoic 1956-5-3
1974-27-3...7
1978-30-67

Metamorphic rocks 1971-20-22
1973-24-37
1978-30-19/58

Methwold (Series) Common 1957-7-4
1971-19-9/12
1978-30-15
1979-31-48

Metrarabdotos moniliferum 1974-27-41

Mew, D. 1977-29-1

Mexico 1967-15-6

Mice 1974-27-39

Michael, E. 1974-27-30/32

Micraster 1957-7-6
1971-20-27

Micritic reef facies 1985-35-24

Micropora 1985-35-39/45/4

Micro ridges 1971-19-14

Microsolena 1985-35-14/16
197/26

Microtus 1972-22-5

Midlands 1971-20-9
1979-31-25

Middle Jurassic rocks 1978-30-8

Middlemiss, F. 1972-22-41
1985-35-18

Middlesex Regional Exam Board 1974-26-18

Middleton stop drain 1978-30-8/16

Mildenhall 1971-19-41
1973-23-6
1974-25-26/28/3

Miller, G.H. 1982-32-41/43..

Miller, W. 1971-20-29

Millner, R.S. 1982-31-2

Mineralogy 1971-20-20
1974-25-3

Minsmere 1982-32-20

Mintlyn Beds 1984-34-12/13 16/18/19/23

Miocene 1956-5-112
1962-11-9
1972-21-3
1974-27-42
1977-29-25/32/33 34/41/42

Mississippi Delta 1967-15-5
1974-27-58

Missouri Coteau 1974-27-56/58

Mistley 1978-30-97

Mitchell, G.F. 1978-30-37/55/74 92/104
1979-31-17/29
1984-34-80/108
1985-35-53/56

Mixed oak forest 1972-22-4

Mlikovsky, J. 1985-35-59

Modiolus 1972-22-16
1979-31-75

Moir, J.R. 1978-30-85/88

Mojsisovicsia subdelaruei 1983-33-7

Moling 1971-19-20

Mollusca 1969-18-17
1972-22-11...31
1977-29-56/57
1982-32-39...50
1984-34-84/86

Monks Eleigh 1978-30-97/102

Möns Klint 1974-27-55

Montlivaltia 1985-35-21

Moore, D.G. 1967-15-6

Moore, E.S. 1959-9-3
1969-18-5

Moran, S.R. 1974-27-59

Moraine 1962-11-7/8

Moredock, H.S. 1974-26-27

Morgan, J.P. 1974-27-58

Morner, N.A. 1979-31-37

Morrison, R.B. 1971-20-37

Morston 1968-16-8
1972-21-8
1972-22-2/3
1978-30-19

Morter, A.A. 1975-27-26/29//32
1984-34-11/31/51
1985-35-20

Mortoniceras 1983-33-14/24

Motacilla flava 1985-35-65

Mottling 1971-19-20
1976-28-10

Moulds 1974-27-29

Mountains 1971-20-22

Mud 1984-34-125/129

Mudflows 1972-21-37/38

Mudstones 1971-20-9
1974-27-4/5/9 11/13
1976-28-35
1979-31-45...68

Muirwood, H. 1969-18-9

Mulletia mulleti 1974-27-30

Mundesley 1955-3-5
1965-13-2
1968-16-2/3
1971-20-29/32
1972-21-35/38/42
1972-22-2/3
1973-23-5
1974-27-52/55..57
1976-28-60
1977-29-5

Mundford 1979-31-50
  1983-33-24

Murphy, P. 1979-31-11...16
  1984-34-124

Muschelkalk 1971-20-3/7/9

Mutabilis 1979-31-54/56/57

Mya 1955-4-4
  1971-20-35/36
  1972-22-17/19
    23/26
  1974-27-36
  1977-29-37/39/40
  1979-30-86/98/102
  1979-31-4/6/8/75
  1982-32-39...50
  1983-33-43

Myrick, R.M. 1973-24-23/33

Mysella 1972-22-15/17
    19/23

Mytilus edulis 1972-21-43
  1972-22-16/22/24
  1974-27-38
  1977-29-38/40
  1978-30-86/95/95
    98/102
  1979-31-4/6/7/8
    41/75
  1983-33-41/42

Nails 1971-19-32

Najas marina 1983-33-67

Nannocardioceras 1979-31-52/60

Nanogyra 1979-31-52...56
    65
  1985-35-15

Narayan, J. 1967-15-3

Nar, River 1978-30-8/13
    15/16

Nar Valley Beds 1956-5-6
  1968-16-8
  1972-21-8
  1973-23-11...24
  1974-27-61/74
  1978-30/16/17/1
  24/31/33/36/113...11
  1979-31-17/23/2
    26...2
  1984-34-111

Narborough 1978-30-11

Narford 1978-30-11/17/1

Nassa reticulata 1957-7-1

Nassarius 1971-20-35
  1972-21-42

Natica 1972-22-16/22
  1978-30-87/99/1
  1979-31-76
  1983-33-41/42

National 1974-26-38
Federation Educational Research

Natro-jarosite 1974-25-30

Nature Conservancy 1971-19-2
  1973-24-3/10/13

Nautiloids 1974-26-47

Nayland 1978-30-97

Neale, J.W. 1978-30-117/118

Negus, P.E. 1985-35-17

Nekron muds 1971-19-17

Neocomian erratics 1957-7-3
  1974-27-63

Neogene 1974-26-48
  1977-29-24/29
  1978-30-119
  1983-33-14

Neohibolites 1957-7-5
  1969-17-7/9

Neolithic 1974-25-28

Neolithyrina 1969-18-9/12
  1973-24-7

Neptunea antiqua 1969-17-6
  1971-20-36

Neptunea antiqua (cont) 1973-23-18
1974-27-39/40/43
1977-29-41/56
1978-30-97/95/96
99/100
1979-31-5/6/76

Neptunea contraria 1982-32-38

Nesses 1976-28-61

Netherlands 1971-20-10/11
1972-21-3/7
1976-28-30
1977-29-29/37
1985-35-43

Netley 1977-29-42

Netta rufina 1985-35-59

Nets 1961-10-5

New Bedford River 1974-25-32

Newbould 1974-26-28

Newbourne 1971-20-36
1977-29-25/36
43/44
1978-30-96

New England States 1974-27-65

Newfoundland 1971-20-4

Newmarket Series 1971-19-9/12

Newton, E.T. 1985-35-57

New Zealand 1967-15-4

Nicholson, H.H. 1985-35-9

Nickless, E.F.P. 1973-23-8
1984-34-108

Nile, River 1977-29-41

Nobles, L.H. 1962-11-8

Nodosaria 1983-33-62

Nodule bed 1973-23-25/26/31
1974-27-21/24
25/26/34
1979-31-69

Nonionella 1983-33-48/60

Non-marine molluscan fauna 1974-27-37/39
1979-31-73

Norden, J. 1973-24-17/33

Norfolk Young Naturalists 1973-24-10

Normania carinata 1978-30-115

Nortcliff, S. 1977-29-21

North Africa 1978-30-88

North America 1974-27-55

North Atlantic 1971-20-2
1977-29-41

North Creake 1974-27-5/12/13
15
1979-31-29

North Denes 1972-21-33

North Downs 1978-30-14

North End Spit 1973-24-20/31

North Fen 1974-25-28

North Lynn 1979-31-60

North Runcton 1974-27-61/63/64
66/69
1979-31-55

North Sea 1956-5-1...6
1967-15-5
1971-20-2...6
1972-21-2...10
37/42
1973-24-43
1974-27-5-37-47
52/58
1977-29-3/33/41
1978-30-22/61
1979-31-1/9/22
43

North Sea (cont) 1984-34-78/106

North Shingle Bank 1973-24-28

North Walsham 1971-20-32
1972-22-39
1977-29-7

North Weir Point 1973-24-15...17
25/28/30

North Western Regional Exam Board 1974-26-20

North Wootton 1984-34-17

Northern Ireland Schools Exam Council 1974-26-16

Norton, P.E.P. 1969-17-3
1972-22-11...31
1974-27-27/37/45
1978-30-81/97
104
1979-31-10/31
33/34/77
1982-31-1/55
1983-33-43/55
1984-34-86

Norvician 1977-29-25

Norway 1961-10-1
1971-20-6
1972-21-7
1973-24-29
1978-30-19

Norwich area 1971-19-24
1973-23-3
1976-28-6
1978-30-13/39/77
96/119
1979-31-24/69/72
1984-34-103

Norwich Brickearth 1974-27-13/39/41

Norwich Crag 1968-16-17
1972-21-7/18/22
26
1977-29-3/23..45
1984-34-86/87

Norwich Castle Museum 1972-22-2/4...6

Norwich Geological Society 1974-25-11

Norwich Horizon 1972-22-12

Nucella 1969-17-6
1971-20-34/36
1972-21-43
1972-22-16/22
1974-27-36/39
40/42
1977-29-38/41
1978-30-84/87
97/100
1979-31-7/8/72
75/76
1983-33-42

Nucleolites 1985-35-14/25

Nuculana 1956-5-2
1957-7-1
1972-22-16/22
1974-27-30
1978-30-86/99/1
1979-31-5

Nuffield Secondary Science 1974-26-34/41

Nyctea scandica 1985-35-54

Nye, J.F. 1962-11-8

Oak 1973-24-9

Oakington Series 1974-25-22

Oakley, K.P. 1959-9-4
1974-25-3

Oakley 1977-29-57

Oaktree Clay 1979-31-45/48

O'Brien, G.D. 1974-27-58/60

Ochetoceras 1985-35-17

Odhner, N.H. 1972-22-30

Odostomnia 1971-20-35

Oele, E. 1971-20-37
1972-21-7/10

Oenanthe 1983-33-67
1985-35-35

Offaster pilula 1971-20-26

Ohio 1974-27-56

Oil wells 1974-27-6

Old Bedford River 1974-25-32

Old Decoy Farm 1974-25-27/28

Old Fen Meres 1974-25-30

Old Hunstanton 1978-30-19/20

Old Lark River 1974-25-33

Olduvai 1984-34-82

Oligocene 1972-21-2
1977-29-30

Ongar Hill 1978-30-10

Oolina hexagona 1979-31-2

Oolitic limestone 1967-15-2
1973-23-27/29/30
1974-27-8/22/24

Ophimorpha 1984-34-15

Open University 1973-23-35...49

Opis 1985-35-14

Ordovician 1969-17-10/11/15

Ore deposits 1971-20-20

Ore, River 1973-24-15...32

Orford 1971-20-34
1973-24-15/20/23
25/30
1976-28-55
1984-34-77/82/92
1985-35-47

Orford, P. 1983-33-54/58

Ornatothyris obtusa 1957-7-5

Oronsaye, W.I. 1977-29-46...55

Orwellian 1977-29-26/36

Ostracoda 1959-9-2
1974-27-31
1978-30-113..118

Ostrea 1955-3-5
1957-6-1
1972-22-43
1974-27-71
1978-30-98
1979-31-13

Otala lactea 1977-29-42

Otoliths 1974-27-44

Oulton 1978-30-57/66
67/72/74

Ouse, River 1971-19-6/39
1974-25-28/31/32
1976-28-30/33
35...37
1978-30-15/23/31
1979-31-65
1982-32-62
1983-33-64

Outney Common, Bungay 1972-21-18/20/21

Overstrand 1968-16-1...3
1972-21-29...40
1972-22-44
1976-28-21/59/61
1977-29-39/40

Oving 1957-7-3

Owen 1984-34-50

Owen and Thurrell, R.G. 1974-27-31/32
1984-34-37

Owenia fusiformis 1982-32-23

Ox 1972-22-8

Oxborough 1978-30-50

Oxford	1974-25-21 1974-26-12
Oxidisation	1971-19-32
Oxytoma pectinatum	1974-27-30
Pacific	1977-29-41 1979-31-1
Padnal Fen	1974-25-28
Pain, T.	1977-29-56/57
Palaeocorystes	1969-17-9
Palaeolithic (implements)	1971-19-41 1974-25-3
Palaeoloxodon antiquus	1969-18-18 1972-22-4...8
Palaeontology	1971-20-20
Palaeozoic	1967-15-2 1969-17-11 1972-21-2 1974-27-4...8 12/13/15/17
Paling, V.R.	1974-26-8
Palm tree	1972-21-2
Palmer	1979-31-36/44/44
Palynological zones	1974-27-34 1978-30-113
Panomya	1977-29-41
Panopaea	1977-29-33 1978-30-100
Paphia	1979-31-75
Paracidaris	1985-35-15/16
Paracrioceras	1969-18-9 1973-23-30/32 1975-27-26/30/31 1983-33-27
Paramoudra Chalk	1959-9-1
Paramoudra Club	1972-22-12
Pararotalia serrata	1983-33-48/57/6 1984-34-85
Paris	1972-21-2 1974-27-30
Parmacella	1977-29-42 1979-31-73
Parmicorbula striatula	1974-27-30
Particle size	1978-30-35
Parting lineations	1977-29-52
Parvicardium	1972-22-17/19
Paston	1965-13-2 1968-16-3 1971-20-29...3 1972-21-18/19/2 1984-34-109
Pastonian	1972-21-17/18 20...22 1972-22-12 1974-27-52 1978-30-81 1979-31-8/9/33 1982-32-48/53
Paterson, T.T.	1961-10-9
Patina	1978-30-58
Patterned ground	1971-19-41
Pavlovia	1979-31-56
Peake, N.B.	1962-11-12 1965-13-7 1968-16-11/17 1969-17-7/8/9 1969-18-6 1971-20-26/28 1973-24-5/14 1974-25-23/35 1974-27-57/60 1978-30-119 1982-32-62 1983-33-27/32 1985-35-71/72

Pearson, I. 1984-34-123..140

Pearson, R.G. 1974-25-35

Peat 1972-21-25
1974-25-27/29
1976-28-22/38/41
1979-31-13/40
1984-34-123/134

Pebbles 1962-11-6/8/9
1963-12-1/2
1966-14-2
1967-15-3
1968-16-18/19
1969-17-7
1969-18-17

Pebbly series 1955-4-2

Pecten 1957-6-1
1977-29-27/34
1978-30-97/98

Pectinatites 1979-31-52...56
60...62/66/69

Pedological sequence 1971-19-9

Peelo Formation 1972-21-8

Pegwell Bay, Kent 1977-29-4

Penning, W.H. 1985-35-6

Penny, L.F. 1974-27-71/75
1978-30-30/37/75

Pentacrinus 1979-31-52/57

Perca 1983-33-77

Perche 1957-7-3

Perdix 1985-35-61

Periglacial cryoturbation 1969-18-18/19
1971-19-12/40
1973-23-11/22
1973-24-41
1978-30-72
1978-31-13

Peringia ulvae 1983-33-42

Perisphinctes plicatilis 1985-35-11

Perkins, P.J. 1974-26-46

Permafrost 1961-10-1...13
1972-21-17/20
1973-23-18/19
1974-27-52
1978-30-61

Permian 1969-17-11
1971-20-2/4/5/6
1974-27-4/13/18

Permo-Triassic 1974-27-7/8

Perrin, R.M.S. 1971-19-42
1974-25-26
1976-28-4/16
1977-29-4/11
1978-30-66
1979-31-23
1984-34-106
1985-35-6/20

Peru 1967-15-4

Pessl, F. 1974-27-65/75

Peterborough 1974-25-27

Pethick, J.S. 1984-34-124

Pewe, T.L. 1973-23-24
1978-30-76

Pettijohn, F.J. 1959-9-1/2

Pettitt, N.E. 1969-18-6
1973-24-14

Phacoides 1978-30-86
1979-31-5/75

Phalacrocorax carbo 1985-35-58

Phillips, F.C. 1978-30-46/54

Phillips, L. 1972-22-4
1973-23-5/6
1984-34-108

Philosophical transactions 1974-25-5

Phi-units 1978-30-57

Phleger, F.B. 1967-15-6

Pholas 1974-27-38
1978-30-100/101

Phosphatic ironstone nodules 1973-23-27/29/30
1974-27-22/25/25
29/34
1977-29-27/35
1978-30-92/93
95/97
1979-31-51
1984-34-73

Phosphatised fish 1973-23-26
1974-25-22
1979-31-55

Phosphorus 1979-31-55

Phragmites 1979-31-11
1984-34-125/130

Picard and High 1977-29-55

Picea 1957-7-2
1972-21-21
1972-22-15

Pictonia rasenia 1979-31-52/56

Piezometers 1976-28-37/43

Pillows 1971-20-9

Pinckney, G. 1984-34-14

Pinna rudis 1972-22-16

Pinus 1957-7-2
1972-21-21
1972-22-15
1974-27-42
1979-31-7
1984-34-86

Pisidium 1974-27-40

Pisolite 1985-35-25

Planorbis 1969-18-17
1972-22-29
1974-27-39
1983-33-40

Plant remains 1978-30-61

Plantago lancaeolata 1972-22-5

Plantation Farm 1974-25-28

Platax 1974-27-40/44
1977-29-38/39
1978-30-87
1979-31-76

Plateau gravels 1978-30-72

Platicidae 1974-27-44

Platt, J.I. 1974-26-5

Pleasure Gardens till 1978-30-67/68
70-72

Plectrophenax 1985-35-64

Pleistocene 1955-3-1
1956-5-1/3
1957-7-1/2/3
1962-11-2
1965-13-4
1967-15-5
1969-17-3/4/5
1969-18-17/18/
1971-19-24
1972-21-4/25
1972-22-15
1973-23-3...9
1978-30-3...38
55...7
1979-31-1/17/.
64
1982-32-2/53
1983-33-45
1984-34-84/131
1985-35-53...6

Pleisiosaur 1979-31-61/67

Pleuromya 1985-35-14

Plicatula 1969-17-7
1985-35-15/26

Pliny 1974-25-3

Pliocene 1956-5-1/2
1962-11-12

Pliocene (cont) 1971-20-35
1972-21-3/6
1973-23-3
1974-27-41/42
1978-30-79
1979-29-25/42
1979-31-73
1982-32-12
1984-34-66

Plunge 1971-19-36

Pluteus Trough 1972-21-4

Podocarpus 1972-22-15

Podoseris 1974-26-48

Podzolization 1971-19-4/9

Poederlian/Merksemian 1956-5-3
1977-29-31

Pointer, P.H. 1973-24-13

Pointon, W.K. 1978-30-55...76

Poland 1967-15-4
1971-20-4

Pollen 1961-10-9
1969-17-4
1972-22-2/5/13
14/15
1977-29-23
1978-30-80
1979-31-71
1984-34-89

Polstead 1978-30-97

Polygons 1961-10-5

Polymorphina 1983-33-60

Polyzoans 1955-3-5
1971-20-35
1975-27-36/41
1977-29-27/30/33
1978-30-87

Popiel-Barczyk 1985-35-41

Porina 1969-17-12
1985-35-45/46

Portman, J.P. 1962-11-9

Portsdown 1967-15-5

Porzana porzana 1985-35-65

Postma, H. 1967-15-5

Postwick 1975-27-40
1978-30-39/85
1979-31-71

Potamogeton natans 1985-33-67

Potter Heigham By-pass 1976-28-42/43

Potton 1957-7-3

Pre-Anglian 1982-32-51...59

Pre-Boreal 1972-21-8

Pre-Cambrian 1971-20-4
1974-27-4/5/10
12/13/15/16/17

Preece, R.C. 1983-33-63...72

Pre-Glacial 1978-30-42/67
72/74

Pre-Ludhamian 1978-30-103

Prestwich, J. 1965-13-1
1972-22-12/30
1977-29-35/45
1978-30-79/80/90
1983-33-35...37
1984-34-69/71
78/87

Pretty Corner, Sheringham 1973-24-37/44

Price, R. 1983-33-3/7/13

Prickwillow 1974-25-28

Prigg 1974-25-26

Pringle, J. 1979-31-48/62/68
1984-34-14

Privet 1973-24-9

Prodeshayesites 1973-23-25/26/30
1975-27-24

Propectinatities 1979-31-52/54

Protocardia morinica 1979-31-57/60

Protoconch 1972-21-41

Protulophila 1985-35-15
64/83/92
1979-31-18/76
1982-32-23/55

Pseudamusium gerardi 1977-29-33

Ptchopotamides icenium 1977-29-37

Pullenia sphaeroldes 1983-33-60/62

Pulmonates 1975-27-39

Puny Drain Setchley 1979-31-48/57
62...65/70

Pupilla muscorum 1983-33-69

Purchas, A.W. 1977-29-46/55

Purple Till 1978-30-29

Purpura incrassata 1957-7-1

Purpura lapillus 1969-18-15/16

Pycnodonte 1971-20-35
1973-24-8

Pyramidellid 1972-22-16

Pyrgo 1983-33-60

Pyripora 1969-17-12

Pyrites 1971-19-32
1973-23-29
1974-27-8/26
1979-31-51/55
1984-34-14

Pyritous nodules 1971-19-32/33
1977-29-30
1979-31-32

Pyrolusite 1971-19-33
1979-31-33

Pyrulina 1983-33-60

Quartz 1959-9-4
1968-16-19
1972-22-13
1974-27-24
1977-29-29
1978-30-22/58
64/83/92
1979-31-18/76
1982-32-23/55

Quaternary 1956-5-6/7
1957-7-2
1965-13-4...7
1966-14-1...7
1968-16-17
1972-22-44
1976-28-29/33/
1977-29-23
1978-30-55/113
1
1979-31-42
1982-32-1...35

Queens Ground, Methwold Fen 1974-25-28

Quenstedtoceras 1985-35-11

Quercus 1957-7-2
1972-21-21
1972-22-15
1979-31-6
1983-33-67

Quidenham 1971-19-39

Quinqueloculina 1978-30-118
1979-31-9
1983-33-57/60/

Radiocarbon dating 1978-30-17

Rafts 1974-27-65

Raia 1978-30-87

Railways 1971-20-32/33

INDEX (1953-85)

Raiswell, R. 1982-32-61...70

Raja 1974-26-44
1979-31-76

Rampart Field, West Stow 1971-19-42

Ramsholt Cliff 1974-25-8
1977-29-24/36
1978-30-80
1984-34-73
1985-35-47

Randall, R.E. 1973-24-15...35
1974-25-15...19

Rangifer tarandus 1972-22-8

Raindrop impressions 1977-29-52

Ranson, C.E. 1961-10-13
1963-12-4...7
1965-13-7/8
1966-14-1...7
1968-16-1...16
1971-19-39/42
1974-27-31
1976-28-4/16/21/27
1978-30-55/73/76

Ranunculus sardous 1983-33-64

Rasenia 1979-31-52/56

Rastall, R.H. 1959-9-3
1974-25-23/35
1983-33-3/16
1984-34-14
1985-35-9/13/19

Ratcliffe, K. 1976-28-67

Rawson, P.F. 1983-33-7
1984-34-11
1985-35-10

Ray, J. 1974-25-4

Rays 1978-30-93
1979-31-75

Rayden 1978-30-97

Rayleigh 1978-30-55

Read, B. 1979-31-43

Read, H. 1972-22-41
1982-32-29

Reading Beds 1969-17-4
1978-30-92

Reclamation 1976-28-35
1984-34-131

Rectithyris 1957-7-5

Red Chalk 1957-7-4/5
1973-23-25
1974-27-32
1978-30-9/19/22

Red Crag 1956-5-3
1971-19-32/33
1972-21-6
1973-23-3
1984-34-82

Red Rock 1966-14-1
1969-17-13
1971-20-11
1983-33-3...26

Redmere 1974-25-31

Reed Bed 1979-31-11

Reeder, D.E.H. 1955-4-1...4

Re-entrants 1977-29-15

Reepham 1974-27-13
1976-28-21

Reeve, J. 1979-31-77

Reid, C. 1956-5-2
1962-11-12
1965-13-1
1966-14-1
1968-16-1
1972-21-18
1972-22-1/12/13
1973-23-3
1974-27-42/52/60
1976-28-12
1978-30-90/93/97
1979-31-58

Reid, C. (cont) 1982-32-1/51
1983-33-35/43
1984-34-69/77

Reid-Moir, C. 1978-30-55

Reindeer 1972-22-5/8

Relief channel 1979-31-80

Rendel 1979-31-36/42/44

Reptile 1979-31-56

Resatrix 1974-27-30

Retusa 1972-22-16/22

Reuverian 1984-84-80

Revetments 1972-21-38

Rhaetic 1971-20-3/9

Rhammatopora 1969-17-13

Rhaxella 1985-35-16

Rhine, River 1972-21-7

Rhinoceros 1969-18-18
1972-22-4/5/8
1974-25-4
1978-30-29

Rhizocorallium 1984-34-18/24

Rhomb porphyry 1978-30-19

Rhynchonellids 1969-18-6...9
1975-27-29/31
1979-31-52/53
57/61/66

Rice, R.J. 1974-27-56
1979-31-19/29

Richter, W. 1962-11-9

Ridding, C. 1977-29-21

Riley, L. 1985-35-10

Rills 1977-29-52

Ringicula 1979-31-76
1983-33-42

Ringiculella 1971-20-35

Ringmere 1971-19-40

Rios, J.M. 1967-15-5

Ripple bedding 1978-30-61/96/

Rising Lodge 1978-30-14

River terrace 1974-25-24

Roach 1973-23-32
1975-27-21/25
26/30/31

Robberds, J.W. 1974-25-8/13

Roberts, T. 1985-35-9

Robertsonites 1978-3-115/116

Robinson, A.H.W. 1972-21-34
1973-24-17

Robinson, J.E. 1978-30-113..1

Rock 1971-19-4
1974-27-3

Rocklands 1979-31-49

Rock salt 1971-20-9

Roddons 1971-19-14
1974-25-27/29/

Rodents 1978-30-87
1983-33-77

Roe, D.A. 1971-20-37

Roman Villa Sites 1971-19-32
1974-25-30/32/
1976-28-35
1979-31-37

Rootlet bed 1974-27-47...

Rosalina parisiensis 1983-33-40/60

INDEX (1953-85)

Rose, C.B. 1969-18-4 1972-22-12/30 1973-23-15/34 1974-25-7/8/10 1979-31-68/118 1984-34-6/26 18/32

Rose diagrams 1978-30-50/51

Rose, J. 1974-27-71 1978-30-74/70 1979-31-58/64 1984-34-90

Rostrocarinate 1978-30-88...90

Rotalipora 1983-33-20

Rotational slip 1972-21-38

Rothamstead 1978-30-97

Rotliegendes 1971-20-3/5 1974-27-8

Rouillieria ovoides 1984-34-15

Roumania 1967-15-4

Roy, P.S. 1984-34-124

Roydon Common 1957-7-5 1978-30-10

Roxham beds 1984-34-12...14

Rügen 1983-33-27..32

Rugia 1983-33-32

Rumbelow, Mr & Mrs 1971-19-41

Runcton beds 1984-34-12/16/17

Runnels 1977-29-47/52

Runton 1955-4-4/5 1977-29-29/39

Rusnak, G.A. 1967-15-6

Rutten, M.G. 1961-10-12 1962-11-9

Saalian glaciation 1956-5-6 1972-21-8 1973-23-7

Saccocoma 1979-31-52...54 57/61...63

Sahni, M.R. 1969-18-9

Saint Cross, South Elmham 1957-7-2 1973-23-4

St. Erth 1977-29-25/32

St. German's Bridge 1979-31-60

St. Ives 1983-33-63...72 63

St. Joseph, J.K. 1973-24-32

Sainty, J.E. 1978-30-88/90

Salt basin 1971-20-6

Salt marsh 1978-30-31 1984-34-125..128

Salt plugs 1971-20-6

Saltation 1977-29-9

Saltern Lode 1978-30-11

Salthouse 1976-28-58 1984-34-132

Salway, P. 1974-25-31/33/35

Salzgitter 1974-27-30

Sam's Cut Drain, Methwold 1974-25-28

Sand 1955-4-2/3 1961-10-6 1963-12-1...3 1966-14-1...5 1967-15-3/4 1968-16-17/19 1969-17-3...5 1969-18-13...18 1971-19-9/14/21 30/32/35...37/41

Sand (cont) 1972-21-18/20
29...40
1972-22-12/21/26
1973-23-22
1973-24-37
1974-25-22/24
1974-27-25/26/30
33/58/65
1976-28-30/38/41
1977-29-4/46/47
52
1978-30-18/58/61
64/67/68/72/77/79/81/93/95/96
1979-31-1/5/31
1982-32-23/24/25
27/71/72
1984-34-18/123..
140

Sandringham 1957-7-4
1969-18-4
1973-23-13/31
1974-25-22/38
1974-27-61-63
1979-31-18/19/50
56/58/60/62/65
1984-34-11/13
14/22

Sandstone 1974-27-7/8/22/24
1978-30-19/22
1979-31-18

Sandy loam & clay 1971-19-9

Santon Series 1971-19-9/12/30

Sardeson, E.W. 1973-23-16...24

Saskatchewan 1974-27-56

Saxthorpe 1974-27-7...9
1978-26-12
1979-31-49

Scalaria groenlandica 1983-33-42

Scalariform 1974-27-40

Scaldesian 1956-5-2
1974-27-43
1977-29-25/30

Scandinavia 1971-20-4

Scaphella lamberti 1972-21-41
1982-32-37

Scaphopods 1974-27-29

Schafer, J.P. 1973-23-24

Schelling, J. 1976-28-20

Schist 1971-19-33
1978-30-19

Schloenbachia varians 1969-17-7

Schools Council Integrated Science Project 1972-21-13/15
1974-26-31/38

Schwarhacher, W. 1985-35-19

Schwarzacher, W. 1984-34-14/25

Schytt, V. 1962-11-8

Scirpus 1983-33-64

Scitulus 1979-31-54/60

Scolt Head 1976-28-57/58
1984-34-126..1
135/13

Scotland 1971-19-33
1971-20-4/13
1979-31-46

Scours 1977-29-52

Scratby 1953-1-5

Scrobicularia 1971-20-35/36
1972-22-23
1975-27-33
1977-29-25/29
37/42
1978-30-86
1979-31-4/11/7
1982-32-44
1984-34-86/126

Scrub 1984-34-131

Scrutton, P.C. 1967-15-6
1985-35-15

Seale, R.S. 1974-25-21...36

Seals 1977-29-39

Searlesia costifer 1978-30-100

Sea walls 1976-28-64

Sedge carr peat 1971-19-17

Sedge Fen Road 1979-31-69

Sedgwick, A. 1985-35-3/4

Sedgwick Museum Cambridge 1974-26-47
1979-31-61

Sedimentation 1967-15-1...6

Seeley, H.G. 1984-34-49
1985-35-11

Seifert, A. 1967-15-3

Seismic refraction 1974-27-3

Sellas, W.J. 1959-9-3

Semicytherura 1978-30-114

Senonian 1957-7-6
1967-15-3
1969-17-14

Septarian nodules/blocks 1973-23-19
1979-31-69

Serinus serinus 1985-35-61

Serpula 1973-24-8
1978-30-101
1979-31-54/55

Serripes 1972-22-17/19/20

Setch 1978-30-16/17

Severn 1965-13-6

Severals House 1979-31-49

Sewage 1973-24-41

Sewerby 1978-30-29
1979-31-25

Shackleton, N.J. 1984-34-80

Shale 1974-27-7/8/9
1979-31-46/53/54
55/57/58/60/62/63

Shalford 1978-30-97

Shark 1978-30-83/85
92/97

Sharp, R.P. 1962-11-8
1973-23-24

Sharpe, D. 1957-6-2

Shear moraine 1962-11-7/8

Shell beds 1969-17-3/4
1972-22-21...24
26...29
1974-27-34/36/37
1978-30-81

Shelly 1978-30-97

Shenley limestone 1957-7-5

Shephard, F.P. 1967-15-5/6

Shepherd's Fen 1974-25-33

Shepperd, E. 1977-29-21

Sheringham 1962-11-12
1972-21-34
1973-23-3
1973-24-37...44
1974-27-57
1976-28-3...27
59/61
1977-29-7/29

Sheringham Waterworks Co 1973-24-41

Shingle Street, Suffolk 1973-24-15...35

Ship burials 1979-19-32

Shippea Hill 1974-25-23/27/31

Shotton, F.W. 1956-5-6
1961-10-4/11

Shotton, F.W. (cont) 1978-30-29/37, 38/76; 1979-31-23/24, 25/29

Shouldham Thorpe 1979-31-58

Shropham 1971-19-39; 1972-22-2/3/6

Shrubhill 1974-25-26

Sidestrand 1965-13-2; 1968-16-3; 1972-21-18/20/22/38/39; 1972-22-12/44; 1974-27-57; 1979-31-9; 1982-32-51...59; 1985-35-42/44

Sietland 1974-25-32

Sieveking, G.de G. 1971-19-41

Silica 1959-9-2/3/4

Silt 1969-18-17; 1971-19-24/27/41; 1972-21-18; 1972-22-12; 1974-27-4/7/9/11, 13/65/67; 1976-28-35/40; 1977-29-3...20; 1978-30-58/72/92; 1979-31-50/57

Silurian 1974-27-9

Simmonds, A. 1976-28-67

Sinodia polytropa 1977-29-33

Sites of Special Scientific Interest 1973-24-3; 1976-28-32

Sitta europea 1985-35-60

Sizewell 1982-32-1...35; 1983-33-54...62; 1984-34-75/82

Skempton, A.W. 1976-28-48

Skenea planorbis 1957-7-1

Skertchly, S.B.J. 1974-25-23/26/3; 1978-30-14/38

Skeyton 1977-29-38/40

Skolithos 1984-34-15/18/

Slate 1974-27-9/11

Slater, G. 1962-11-7/10/1; 1974-27-60

Slaughden 1973-24-29

Slindon Sands, Sussex 1978-30-117

Sluiter, J.W. 1973-24-14

Slumping 1973-24-44

Smith, D.B. 1966-14-1/3

Smith, D.I. 1971-20-38; 1973-24-16/33

Smith, W. 1958-8-1/2; 1974-25-6/8; 1979-31-45/48, 68/71; 1984-34-9

Smith, W.E. 1967-15-3

Snettisham 1973-23-25...2, 30/31; 1984-34-27/28, 30...

Soakaways 1976-28-33

Sodium Hexametaphosphate 1977-29-7

Soham 1974-27-4/10; 1979-31-49

Soil drainage classes 1971-19-6

Soil forming process 1971-19-4

Soil profile 1971-19-4

INDEX (1953-85)

Soils	1971-19-2/30 1973-24-43
Soil series	1971-19-4
Soil survey	1971-19-2...31 1974-25-37 1976-28-4 1977-29-3
Sola, M.A.	1974-27-3...19 1978-30-105..112 1985-35-6
Solifluction	1956-5-6 1973-23-22 1976-28-18 1977-29-20 1978-30-36
Solomon, J.D.	1968-16-5 1972-21-35 1972-22-2/21 1974-25-23/36 1976-18-4/27 1978-30-19/38
Somateria gravipes	1985-34-59
Somerton	1974-27-8...10 1979-31-49
Sorgenfrei, T.	1972-22-28
Soutendam, C.T.A.	1982-32-24
South Pickenham	1978-30-52
South Pier	1972-21-33
South Shingle Bank	1973-24-30
South Wootton	1978-30-23 1979-31-58
Southern Regional Exam Board	1974-26-22
Southern Universities	1974-26-16
Southery	1974-25-22 1978-30-15/32 1979-31-46/48/57 64/69 1985-35-16/19
Southgate	1978-30-111
Southwold	1977-29-28 1982-31-2/3/12 20 1982-32-56
Sowerby, J.de C.	1974-27-30/32 1979-31-71
Spain	1967-15-4
Sparid	1979-31-76
Sparks, B.W.	1972-22-4/5 1973-23-7/9 1974-25-26/35 1976-28-4/27 1978-30-13/33 1979-31-26/29 1984-34-92
Spath, L.F.	1973-23-34 1984-34-31 1985-35-11
Speeton clay	1957-7-4/6 1971-20-9 1983-33-13
Spencer, H.E.P.	1971-19-32...34 1971-20-39 1978-30-93/95/104
Sphaerium	1969-18-18
Sphagnum	1972-22-15
Sphenia	1972-22-17/23
Sphenotrochus	1978-30-101
Spice Chase	1978-30-11
Spilsby sandstone	1957-7-4 1985-35-19
Spirotropis	1971-20-35
Spisula	1971-20-35 1972-22-15/17 19/23/24 1974-27-36 1978-30-86/100 1979-31-6/8/75 1983-33-41

Spitsbergen	1962-11-8 1974-27-65 1978-30-67/68
Spondylus	1957-6-1 1973-24-8
Sponge	1959-9-2 1985-35-38
Spongia paradoxica	1972-22-43 1983-33-7
Spotted Hawkweed	1973-24-9
Springs	1973-24-41
Sproxton	1974-27-5
Stachys sylvatica	1983-33-67
Stalham	1977-29-7
Stamford	1971-19-39
Stansfield, R.	1982-32-50
Start Point, Devon	1972-21-3/4
Stather, J.T.	1962-11-10
Staurolite	1957-7-4 1974-25-23
Stebbings, R.E.	1973-24-8...11 13/14
Steers, J.A.	1973-24-16/30/33 1977-29-46/49/55 1979-31-11 1984-34-93/136
Steinich, G.	1983-33-32 1984-34-124/136
Steinkerns	1974-27-29
Steinmetz, R.	1974-27-69/75
Steps	1961-10-5
Stereographic projections	1978-30-46/47/50
Stevens, L.A.	1974-25-24/36 1978-30-16/113
Stevens, L.A. (cont)	1979-31-19/23 26/29 1984-34-111
Stiffkey	1972-22-2 1984-34-132
Stoke by Clare	1978-30-97
Stoke Ferry	1957-7-5 1978-30-11/13 14/52
Stoliczkaia dispar	1983-33-11/15
Stonea	1974-25-24
Stone beds	1972-21-43 1972-22-44 1974-27-34/36/ 1978-30-83/90
Stone orientation	1973-23-6
Stony Stratford	1978-30-12
Stourport	1965-13-6
Stow Pumping Station	1979-31-69
Stow Bedon	1971-19-39
Stowbridge	1978-30-23/24 1979-31-61/62 67/70
Stow Market	1956-5-3 1978-30-92
Stradbroke	1969-18-13... 1972-21-4/6/2 1977-29-32 1978-30-103 1982-32-42/44 1983-33-45... 1984-34-85
Stratford	1978-30-97
Straits of Dover	1971-20-2
Strauch, F.	1974-27-45

Stratigraphy 1954-2-2
1971-20-21
1973-23-3...9

Straw, A. 1968-16-4
1973-23-6/8
1976-28-4/8/14
1978-30-30/38
1979-31-17...30
1984-34/106/113

Stream Channels/Valleys 1971-19-14
1978-30-40/42

Streblus beccarii 1956-5-3

Striae 1962-11-10

Stride, A.H. 1967-15-4
1971-20-39

Stripes & Polygons 1961-10-5
1971-19-12/14
21/30/36
1973-23-3

Stuart, A.J. 1972-22-5
1983-33-69/75
1985-35-59

Stubblefield 1974-27-18

Stuntney 1974-25-21/23
24/26/28

Sturnus vulgaris 1985-35-58

Sturston 1979-19-39

Suaeda fruticosa 1984-34-25/130

Sub-aerial weathering 1974-27-34

Sub-Atlantic 1972-21-8

Sub-Boreal 1972-21-8

Subcraspedites 1984-34-17/19

Sub-glacial 1978-30-42

Sub-littoral 1972-22-19

Sub-Mesozoic floor in Norfolk 1974-27-3...19
10/13...15
1978-30-105

Sub-Permian 1974-27-3

Subsoil 1971-19-4/21
1973-24-44

Sudbourne 1971-20-35
1985-35-47

Sudbury 1977-29-42
1978-30-97/102

Suffolk sands and gravels 1971-19-32...34
1974-27-38

Suffolk Trust for Nature Conservation 1971-19-41

Suggate and West, R.G. 1978-30-32
1984-34-113

Superior Oil Co. Ltd 1974-27-17

Supracorallina 1979-31-52

Surlingham 1985-35-39

Surlyk, F. 1983-33-32
1985-35-11

Surrey 1979-31-56

Sustead series 1973-24-43
1976-28-10

Sutneria 1979-31-52/55/56

Sutton 1974-25-11/22
25/26
1974-27-4/9
1977-29-24/35
1984-34-75/76

Svennson, H. 1962-11-10

Swaffham 1971-19-6
1978-30-39

Swanscombe 1985-35-61/62

Swanton Morley 1972-22-2...4
1973-23-5

Sweden 1962-11-10
1979-31-37

Sweeting 1974-26-4

Swinnerton, H.H. 1974-27-31/32
1984-34-9

Sycamore 1973-24-9

Sykes, R.M. 1985-35-11

Syleham 1972-21-25...28

Sylter Crag 1977-29-42

Sylvester-Bradley, P.C. 1974-27-18

Sylvia borin 1985-35-61

Synoptical table 1974-25-5

Taber, S. 1973-23-24

Tadorna tadorna 1985-35-64

Tallantire, P.A. 1971-20-37

Tarr, W.A. 1959-9-4

Tasselia ordami 1977-29-35

Tas, River 1985-35-1...4

Tat, River 1978-30-49/53

Tatler, W. 1971-20-38
1973-24-44
1977-29-3

Tattershall 1979-31-24

Tattingstone 1977-29-24
1985-35-47

Tavener-Smith 1969-17-14

Taylor, B.J. 1962-11-10

Taylor, J.E. 1965-13-7

Taylor, J.H. 1961-10-11
1967-15-2
1969-18-5

Taylor, J.H. (cont) 1971-20-37
1985-35-6/16

Taylor, R.C. 1974-25-6..8/1
1974-27-42/45
1979-31-71/73
74/77

Taylor, S.H. 1974-25-21

Teaching Geology 1971-20-17...2
1972-21-12

Teall, J.J.H. 1984-34-6/46
1985-35-18

Tectonics 1962-11-1...16
1968-16-3
1972-21-6

Teeth 1969-18-18

Tellinid 1957-7-1
1972-22-23/24

Terebratula 1956-5-2
1957-7-5
1969-18-9
1974-26-47

Terebrimya 1974-27-30

Teredolites 1974-27-30

Tempskya schimperi 1957-7-4

Terraces 1971-19-6/14/
1973-23-6

Tertiary 1956-5-3
1962-11-9
1967-15-2
1969-17-14
1971-20-2/8
1972-21-2
1974-27-37/41
1978-30-93

Tetrae urogallus 1985-35-62

Tetrastes bonasia 1985-35-62

Texas 1967-15-6

Texel, Netherlands 1979-31-43

Textularia suttonensis 1983-33-46/48
52/60

Textures 1971-19-4

Thalassinoides 1969-17-7
1983-33-17
1985-35-25/43

Thames, River 1972-21-7
1977-29-4

Thanet Sands 1972-21-2
1978-30-92

Thaxted 1978-30-97

Theodolite 1977-29-13

Thermal contraction 1979-31-31

Thet, River 1971-19-39
1982-32-62

Thetford Heath 1961-10-10
1971-19-40
1982-32-61

Thetis minor 1974-27-30

Thixotropic 1976-28-42

Thomas, H.D. 1969-17-13

Thompson, D.B. 1971-19-39
1974-26-3...46

Thorney Hill 1974-25-23/26

Thornton, M. 1984-34-103..122

Thorpe 1974-27-44

Thorpe Aldringham 1972-21-18/19
21/22
1974-27-40/44
1977-29-38

Thorpeness 1982-31-1/3/8/20
1984-34-75

Thracia 1979-31-75

Thrust raft structures 1974-27-55

Thunder Lane Pit 1961-10-10

Thurne Valley 1976-28-42

Thurnian 1972-22-12/15
1978-30-96
1983-33-54

Thurrell, R.G. 1984-34-37

Tidal currents 1972-21-6

Tiglian 1977-29-25/37/39

Tile draining 1971-19-20

Tilia 1957-7-2

Till, basement 1978-30-29/36

Till, Chalky 1955-4-4/5
1961-10-11...13
1966-14-1
1968-16-1/3/4
1971-19-35
1978-30-19/113

Till, marsh 1978-30-29

Till, sandy 1965-13-1/2
1972-21-41
1975-27-56/61..75
1978-30-58/61/64
1979-31-17/33

Titchwell 1984-34-126/127
234

Tooley, M.J. 1979-31-35/37
39/42/44

Tomlinson, M.E. 1965-13-4...7

Torgerson, T.L. 1974-26-27/43

Torrens, H.S. 1985-35-6/11

Torynocrinus 1974-26-48

Tottenhill 1978-30-17/23/24
31/34/36
1979-31-25
1984-34-116

Totternhoe Stone 1969-17-7
1974-25-23/38

Tottington 1971-19-39
1978-30-50

Toynton, R. 1978-30-39...54
119

Trace fossils 1985-35-38

Trafford Estate 1978-30-78

Tranter, M. 1982-32-61...70

Trenn, T.J. 1974-25-11

Trent 1978-30-12

Trepostomata 1969-17-11

Tressarolax 1974-27-29

Triassic 1969-17-14
1971-20-5/7/8/11
1978-30-8/15/19
1979-31-24

Tricart, J. 1973-23-13...24

Tricephalopora 1985-35-45

Trigonia 1969-17-9
1969-18-4
1974-25-22

Trilobites 1971-20-21

Trimingham 1957-6-3
1962-11-12
1972-21-35
1974-25-7
1974-27-57
1976-28-66
1984-34-113/115

Trimmer, J. 1965-13-1
1978-30-55/76

Tringa ochropus 1985-35-60

Trinidad 1967-15-5

Tritton 1979-31-42/44

Trivia 1978-30-98

Trochammina 1979-31-15

Tropaeum 1973-23-26
1974-27-24

Trueman, A.E. 1971-20-17
1972-22-37/38

Truncatellina 1983-33-69

Trunch 1979-31-49

Trypanites 1985-35-14

Tsuga 1972-21-20
1972-22-15

Tuff 1974-27-5

Tunisia 1967-15-5

Tunnel valleys 1978-30-13/15/
1979-31-20

Turdus 1985-35-60

Turner, C. 1972-22-5
1978-30-92/113
118

Turonian 1967-15-3
1969-17-9/14

Turritella 1957-7-1
1972-21-41
1977-29-37
1978-30-84/87
95/96/
1979-31-5/76
1984-34-77

Tutin, T.G. 1983-33-64

Twenhofel, W.H. 1959-9-3

Twente Formation 1972-21-8

Tyler, R.W. 1974-26-27

Tyrrhenian 1957-7-1

Ubaghsia crassa 1983-33-27...

Ugg Mere 1974-25-27

Ulmus 1957-7-2
1972-21-21
1972-22-15

Underground stream 1972-21-37

University of East Anglia 1968-16-17...21
1973-24-10
1974-27-10/11

Upper Campanian 1969-18-6/12

Upper freshwater bed 1972-21-17
1977-29-32

Upper Jurassic cementstone and shale 1978-30-5
1979-31-18/21

Upper Silurian 1974-27-4

Upware 1957-7-4
1985-35-3...38

Upwood 1974-27-4/12

Uria aalge 1985-35-58

Ursus 1978-30-95
1983-33-74/77/78

Vagners, U.J. 1974-27-66/74

Valanginian 1984-34-21/26

Valentin, H. 1972-21-37/40

Valley Floors 1971-19-27

Valley Gravels 1971-19-17
1974-27-39

Vallonia 1974-27-39
1983-33-69

Valvata piscinalis 1972-21-42
1979-31-8

Van Andel, Tj.H. 1967-15-5/6

Van Straaten,M.J.U. 1967-15-5

Van Voorthuysen, J.H. 1956-5-2
1977-29-45
1984-34-77

Vancouver, C. 1985-35-20

Veenstra, H.J. 1977-29-4/22

Veluwe type 1974-27-55

Venerupis 1972-22-23
1978-30-96/98

Ventriculites 1957-6-1
1985-35-39

Ventris, P.A. 1983-33-63...72

Venus 1957-7-1
1972-22-23
1978-30-84/86
98/99/100/101
1979-31-4/75

Vertebrates 1974-27-44
1978-30-83
1979-31-69
1983-33-69/70
73...80

Vertigo pygmaea 1983-33-69

Villagranchian fauna 1971-19-33
1978-30-95

Vincent, C.E. 1976-28-67
1984-34-124

Vinegar Middle 1978-30-10

Vink, A.P.A. 1976-28-27

Virgatopavlovia 1979-31-56

Visean 1974-27-8

Visher, G.S. 1978-30-68/76

Vivianite 1979-31-55/69

Viviparus medius 1974-27-40
1977-29-37
glacialis 39
1979-31-76
1983-33-42

Voigt, E. 1985-35-43...45

Volcanic agglomerate 1974-27-4

Voles 1972-22-5
1974-27-39/40
1977-29-37/39

Volutes 1972-21-2
Vulliany, D.M.H. 1973-24-32
Waddingham, S. 1976-28-67
Walberswick 1982-32-8
Waldringfield 1971-20-36
1978-30-96
Walker, J.F. 1985-35-18
Wall, D. 1969-17-3
Wallich 1959-9-3
Walmsley 1971-20-3/6/8
Walton on the Naze 1971-20-34
1977-29-25
1978-30-85
Waltonian 1977-29-26/27
35/42/44
Wangford 1971-20-34...36
1977-29-26/28
1982-32-42/44
Warboys 1974-27-4/12/13
29
Warburg, E.G. 1983-33-64
Warren, S.H. 1978-30-89/91
Wash 1973-23-26
1974-25-33
1974-27-11/13..15
17/71
1976-28-53/66
1978-30-22/30/32
34/105...112
1979-31-21/22
46/50
1984-34-12/21/22
1985-35-18
Wash storage and feasibility study 1978-30-4
1979-31-50
Washburn, A.L. 1961-10-1/4/6/11
1973-23-24
1979-31-33/34

Wassey, Haute Marne 1974-27-30
Waste disposal 1973-24-41
Water 1982-32-61...7
Watershed 1978-30-42
Watertables 1971-19-6/20/2
33/39
1978-30-40
Watlington 1979-31-58
Watson, E. 1973-23-15/23
Watt, A.S. 1961-10-4/10
1971-19-41/42
Waveney, River 1971-19-14
1972-21-29
1973-23-6
1979-31-35
1984-34-113
Weald 1972-21-2/3
Wealden Sands 1957-7-3
Weathering 1971-19-2/3/4/
1974-27-34
1978-30-42/46
Webster 1979-31-45
Wedd, C.B. 1985-35-10/13/
Weeley 1974-27-4/9
Weichselian 1972-21-8
1972-22-8
1973-23-3
1974-25-25
1974-27-56
1977-29-4
Weir, A.H. 1977-29-
Wellman, H.W. 1967-15-4
Wells, C. 1971-20-37
1972-22-6

INDEX (1953-85)

Wells, Norfolk 1976-28-28
1977-29-46
1978-30-49

Welney 1974-25-30/32

Welsh Joint Education Committee 1974-26-12/22

Welton le Wold 1979-31-20/24/25

Wenlock 1971-20-21

Wensum, River 1969-18-17
1973-23-6
1978-30-49/50/53
1984-34-111

Werner, A. 1974-25-11

West Beckenham 1976-28-6/8/10/12

West Bilney 1978-30-11/17

Westgate, J. 1963-12-1...4

West Midlands Regional Exam Board 1974-26-24

West. R.G. 1956-5-6/7
1957-7-2
1961-10-9/12/13
1962-11-8/10
1965-13-1...4/7
1966-14-1
1968-16-8/9/10
1971-19-42
1971-20-
1972-21-7/8/10
17...23
1972-22-2/11/15
21/22
1973-23-3...9/24
1974-25-26/36
1974-26-27/46
1975-27-34/47...
53/69
1977-29-44/45
1978-30-37/55/58
64/72/76/80/91/118
1979-31-19/23/30
31...34/77
1982-32-1/2/4/44
45/54/55
1983-33-43/46
54/55

West, R.G. (cont) 1984-34-71/107

West Row 1971-19-41

West Runton 1965-13-2
1968-16-3
1972-21-18...21
42
1972-22-44
1973-23-3
1974-27-52
1982-32-42/45
1984-34-110

West, R.W. 1974-26-31/32

West Schelde, Netherlands 1974-27-44

West Tofts 1978-30-11/50

West Walton 1978-30-11

West Water 1974-25-31

West Winch 1978-30-23-24
1979-31-58

Westland Green Gravels 1982-32-53/57/58

Westleton beds 1971-19-33
1972-21-22
1977-29-28
1978-30-79/102
1979-31-31/33
1982-32-2/56

Weston Ditch 1974-25-23

Westphalian 1974-27-8

Weybourne 1956-5-6
1962-11-12/14
1965-13-1/7
1968-16-3
1969-18-9/11
1972-21-17/22/34
35/43
1972-22-44
1973-23-3
1973-24-5/43
1974-27-44/55/57
1976-28-8/10/12
21/59

Weybourne (cont)	1977-29-25/27/28 20/38/39 1978-30-49/77/80 81/84 1979-31-9/24 1983-33-27/32 1984-34-123 1985-35-71/72
Whales	1977-29-35
Whalley, P.E.S.	1974-25-4/13
Wheatleyensis	1979-31-56/57/62
Whin sill dolerite	1978-30-19
Whitaker, W.A.	1969-18-15/16 1973-23-26/32/34 1974-25-26 1974-27-4/5/18 52 1978-30-17/23/23 38/93/97/104 1979-31-58/64/68 1983-33-4 1984-34-6/9/27 75
White, P.C.S.	1971-20-38
White ballast	1978-30-92
White Bridge, Southery	1979-31-69
Whitehead, P.J.P.	1974-25-3/13
Whitehead, T.H.	1969-18-5
Whitlingham	1961-10-9 1974-27-40/44 1977-29-26 1978-30-85/88 1979-31-71
Whittlesea, P.S.	1983-33-27...33 1985-35-39...46
Wickham Market	1978-30-92
Wiggenhall St. Peter	1978-30-11 1979-31-57...60
Wigley, T.M.L.	1982-32-67

Wilbertopora	1969-17-13
Wilkes, P.F.	1976-28-29...48 1977-29-59
Wilkinson, I.P.	1983-33-24 1984-34-77
Williams, R.G.B.	1971-19-41/42 1973-23-22/24 1973-24-33 1974-26-4/45
Williams, W.W.	1973-24-16
Willis, E.H.	1974-25-28-36 1974-26-4/46
Wills, L.J.	1974-27-3/5/7 9/13
Wilmington sands	1967-15-5
Wilson, D.G.	1972-21-17/23 1978-30-55/64 72/76
Wilson, R.C.L.	1973-23-35...4
Wilson, V.	1974-26-5
Wiltshire, T.	1973-23-25/34 1979-31-45/46 1984-34-49
Wimbotsham	1978-30-23
Windborne deposits	1976-28-18
Windmills	1976-28-33
Wingfield, I.B.	1972-21-28
Wingfield, R.T.R.	1978-30-38 1984-34-38
Winkelmolen, A.M.	1977-29-
Winterton	1972-21-31 1976-28-61
Wisbech	1978-30-11

Wissey, River 1971-19-39
1978-30-11/15/31
50/52
1979-31-48/69

Witham, River 1979-31-19

Woldstedt, P. 1956-5-6
1965-13-1

Wolferton 1978-30-18
1979-31-22
1984-34-18

Wollemann, A. 1974-27-32

Wolman, M.G. 1978-30-70/75

Wolstonian stage 1965-13-4
1973-23-5/6/7
1974-25-38
1978-30-5
1979-31-17/22/23
24/27/28

Wolterton Park 1976-28-10

Wood, C.J. 1985-35-41

Wood S.V. 1974-27-45
1977-29-56/57
1978-30-78/80
1979-31-9/72/77
1982-32-1/53
1984-34-69/75

Wood Fen 1974-25-29

Woodbridge 1978-30-93

Woodland, A.W. 1956-5-1/3
1971-20-39
1972-21-4/10
1973-23-8
1978-30-13/15/38
40-54
1979-31-19/20
1983-33-45
1984-34-92

Woodrow, J. 1973-24-13

Woods, H. 1974-25-14

Wood's End 1979-31-71

Woodstone 1978-30-33

Wood fragments 1969-17-6
1974-27-29

Woodward, B.B. 1974-25-9
1983-33-69

Woodward, B.H. 1974-25-9

Woodward, H.B. 1969-17-3
1972-22-12/13/31
1974-25-5/9
1974-27-42/46
1976-28-3/8/21
27
1978-30-77/79
80-84
1979-31-9/72
74/77
1982-32-53
1985-35-9/10

Woodward, Henry 1974-25-9

Woodward, H.P. 1974-25-9

Woodward, John 1974-25-4

Woodward, Martin 1974-25-9

Woodward, Samuel 1958-8-2
1965-13-1
1974-25-5...10
1984-34-69

Woodward, S.P. 1974-25-9

Wooldridge, S.W. 1956-5-2

Worlington series 1969-17-8/9
1971-19-9/12/30

Wormegay 1978-30-31

Worssam, B.C. 1971-20-37
1974-25-21/22/26
31/32
1985-35-6/9/16

Wortell 1972-22-2/3/5
1973-23-6

Wragby 1979-31-21...25

Wretton	1972-22-2/3/4 1978-30-33
Wright, C.W.	1957-6-3 1983-33-13
Wright, H.E.	1962-11-11
Wroxham	1978-30-77/91 1979-31-6/8/9
Würm	1966-14-2/3
Wyatt, R.J.	1979-31-19/30
Wybostan	1974-27-10
Wymer, J.J.	1979-31-23/30
Xenostephanus	1979-31-52
Yapp, W.B.	1985-35-62
Yare, River	1954-2-2/3 1968-16-17...21 1972-21-29 1976-28-41 1977-29-28/38 39/44 1978-30-13/85 1979-31-35...44 1984-34-103
Yariv, S.	1982-32-66/69
Yarmouth	1969-17-3...6 1972-21-29...40 1974-25-7 1976-28-47/61/66 1977-29-26/32 1984-34-103
Yehle, L.A.	1961-10-9
Yellowly, Dr.	1974-25-8
Yoldia	1972-22-16/22 1974-27-38 1977-29-29 1978-30-86 1979-31-6/75 1983-33-42
Yonge, C.M.	1972-22-3
Yorkshire	1971-20-10/11 1972-21-37 1974-26-22 1979-31-45
Zaandam	1956-5-2/3
Zagwijn, W.H.	1977-29-45 1984-34-77
Zalasiewicz, J.A.	1984-34-65...1
Zechstein	1971-20-3/6/8/
Zeeland	1977-29-27/38
Zeist	1956-5-2/3
Zim and Shaffer	1972-22-40
Zirphaea	1974-27-34 1978-30-98
Zoophycus	1969-17-7 1985-35-39
Zostera	1984-34-129

Bull. geol. Soc. Norfolk, **36**, 77-88 September 1986

DID THE CHALK POTSTONE WORMS 'SMOKE' H_2S?

B.M. Funnell*

ABSTRACT

It is argued that, if the trace fossil Bathichnus paramoudrae, which is found in the centre of flint potstones (or paramoudras) was produced by a chemoautotrophic vestimentiferan Pogonophore worm, similar (but not identical) to the hydrothermal vent tube worm Riftia pachyptila, a plausible physiology, metabolic system and life-style can be inferred for the worm which is capable of explaining most if not all the observations hitherto made on the trace fossil and its diagenetic associations.

INTRODUCTION

Riftia pachyptila Jones is one of a number of unusual organisms which were recently found congregated around hydrogen sulphide-emitting hydrothermal vents in the deep ocean (Ballard 1977). Subsequent investigations have shown (Cavanaugh et al. 1981) that these worms are probably chemoautrotrophs depending on the H_2S from the hydrothermal vents as their principal source of energy. Detailed observations by Cavanaugh et al. (1981) suggest that conversion of CO_2 (obtained from the ocean water) to organic C compounds (biomass) is carried out by symbiotic sulphur-oxidising prokaryotes (bacteria) in an organ in the worm known as the trophosome. The worm has an excellent vascular system (the trophosome itself is highly vascularised), and a high oxygen affinity haemoglobin, whose oxygen-carrying capacity is relatively unaffected by either changes in temperature or CO_2 concentrations. The haemoglobin occurs both in the

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vascular blood and in the coelomic fluid of the worms (Arp and Childness 1981, Wittenberg et al. 1981). Therefore it is very efficiently equipped for transporting both oxygen and carbon dioxide to and from different parts of the body, including to and from the trophosome, the site of autotrophic (symbiont chemautotrophic) metabolism. The H_2S, which is also required by the sulphur-oxidising symbionts, may also be carried by the blood stream (Cavanaugh et al. 1981, p.341, Wittenberg et al. 1981, p.344), having been acquired by diffusion across tentacular surfaces, (the worms have an anterior tentacular plume which they extend into the overlying water), or it may be acquired directly by diffusion across the body wall of the worm into the coelomic fluid (Cavanaugh et al. 1981, p.341).

The vent worms are up to 1.5 metres long and 35 to 40 millimetres in diameter. They have no mouth and no gut. The only other possible source of nutrition, besides the autotrophic process described, and o its own considered inadequate to support such large organisms, is th uptake of molecular "food" (e.g. amino acids) from seawater via th anterior tentacular plume (Jones 1981).

POTSTONES

Potstones (also called paramoudras) are cylindrical flints, ofte about 0.7 metres in diameter and about 0.7 metres high, usually wit cores of hardened (lithified) chalk. They are common in the Beesto Chalk at Caistor St. Edmunds quarry (TG238046) and on the coast a Weybourne (Peake and Hancock 1961). They also occur in the Chalk o Northern Ireland, Denmark and elsewhere. A very full description o paramoudras, their occurrence, associated trace fossils and altere chalk was given by Bromley et al. (1975). They describe: (a) th variations in form of the flint cylinder, (b) the lithificatio (cementation) of the chalk core, with preservation of moulds of aragonite fossils such as gastropods (as in hard grounds); the lithified core often shows a central grey zone containing disseminated iron sulphide, although this may in some examples be weathered (oxidised) to limonite (iron oxide), (c) a small (5-10 mm) central tube of pyrite (again sometimes oxidised to limonite) or glauconite, defining the burrow of the trace fossil Bathichnus paramoudrae Bromley Schulz and Peake. The burrow is very long (approximately 5 to exceptionally 9 metres) and vertical. (The flint cylinders themselves are rarely continuous over such vertical distances, but may be stacked one above the other over such a range.) The burrow sometimes shows lateral (horizontal extensions), which may be branches, but could also be successive positions of a lower termination. Bromley et al. (1975) speculate that these traces could be the burrows of exceptionally long Pogonophore or Nermertinean worms.

Clayton (1982b) described the trace element and isotopic composition of the central chalk core of a potstone from Norfolk and compared it with the normal chalk outside the flint cylinder. His analyses show that Fe (iron) and Mg (magnesium) decreased away from the central tube (or burrow); that Al (aluminium), P (phosphorus), and to a certain extent K (potassium) were enriched in the normal, unlithified outside chalk compared with the lithified core chalk; that Sr (strontium) was more or less unchanged; and that the stable oxygen isotope composition of the lithified chalk core was similar to that to be expected in normal marine waters. He drew a number of conclusions from these results. He suggested that the Fe was most enriched nearest the central burrow because of the generation of sulphide (subsequently combined with Fe to form pyrite) as a by-product of the bacterial oxidation by sulphate-reducing bacteria of organic matter associated with the worm. He attributed the depletion of Al in the central core to its dilution by the growth of carbonate cement, during lithification. The enrichment of Mg in the central core is likewise also attributed to the growth of the carbonate cement but this may not be the only influence on the distribution of Mg. The stable oxygen isotope composition of the chalk core and its cement is consistent with the cement being precipitated from normal marine pore water rather than from bicarbonate produced by the activity of sulphate-reducing bacteria. In a brief consideration of the process of silicification towards the end of his abstract (a subject further developed in relation to all flint formation in Clayton 1982a), he (1982b) draws attention to the likely effect of the release of H_2S by sulphate-reducing bacteria in accumulating chalk, where it would have been unbuffered by Fe. In most sediments H_2S released by sulphate-reducing bacteria is rapidly converted to iron sulphide by reacting with abundant and therefore readily available Fe. Chalk as a sediment is remarkably deficient in Fe, and there is no reason to think that this deficiency was not primary. Therefore in chalk, as it accumulated, H_2S would have been free to diffuse through the sediment. Clayton argues that the H_2S would have interacted at the boundary between the anoxic sediment (in which it was produced) and the oxic sediment (subject to the burrowing action of benthos bringing in oxygen from the sea-water above) to form acid conditions that would both dissolve calcite and promote the precipitation of dissolved silica; leading thereby to the replacement of carbonate by silica, the first stage in the creation of flint. In the case of potstones the zone of such interaction forming the basis for flints would be set a a radial distance from the locus of sulphate-reducing bacterial action (assumed to be associated with the worm burrow), rather than at a set distance from the sea-floor sediment surface, as in the case of normal horizontal, nodular or tabular flints. In this way the cylinder of flint around the worm tube could be explained.

A NEW INTERPRETATION

If we take what we now know about the physiosology and metabolism of deep-sea vestimentiferan Pogonophore worms found associated with hydrothermal vents ("black smokers") and apply it to the observational and geochemical data published by Bromley et al. (1975) and Clayton (1982b) respectively, it is possible to elaborate an explanation of potstones and their associated trace fossils and diagenesis which accounts for almost all their recorded characteristics.

If vestimentiferan Pogonophore worms existed on the chalk sea-floor they would have been remarkably adapted to utilising the free supply of H_2S existing below the oxidised zone in the almost uniquely iron-free chalk sediment. In other words they could via their symbiotic chemoautotrophs have been trapping the energy potential of the free sulphide of the deep anoxic zone, whilst keeping, by virtue of their very long bodies, their tentacular plumes in the oxidised ocean water at or above the sediment surface. If we make this assumption, almost all the observations so far made on potstones fall into place, and a sequence of four diagenetic zones or stages in the accumulating chalk can be envisaged.

1. Active (oxidised) sediment zone

This is the surface sediment zone in which sediment-feeding, burrowing organisms were ingesting and feeding on organic materials that had accumulated, along with biogenic (skeletal) carbonate debris, on the

Chalk sea floor. This zone in the Chalk, judged by the depth of Thalassinoides burrow systems produced by sediment feeding crustacea, extended to 1 to 1.5 or even 2 metres below the sediment surface (Bromley et al. 1975). In this zone the Pogonophore worm could have adsorbed O_2 and CO_2 from the interstitial water (as well as from the overlying sea-water via its tentacular plume), and circulated it around its body via its efficient vascular system. Both O_2 and CO_2 are readily transported in this way in the Pogonophore bloodstream (see above). The O_2 would have been needed for respiration, but equally a high partial pressure of CO_2 in the bloodstream would have been beneficial for the symbiotic chemoautotrophs, who would use the carbon from the CO_2 to synthesise additional biomass. Removal of CO_2 (more accurately HCO_3^-) from the interstitial water immediately adjacent to the worm would have been liable, as those waters are likely to have been saturated with calcium carbonate, to cause some calcium carbonate to precipitate as a cement. Hence we can imagine initiation of cementation of the central core of the lithified chalk around the worm tube at an early stage in the diagenesis of the sediment as is confirmed by the preservation in it of moulds of aragonitic fossils.

2. Inactive (locally oxidised) sediment zone

Below the zone of active oxidation, say below 2 metres, the body wall of the Pogonophore worm would be in contact with now undisturbed and potentially anoxic sediment, probably containing a sulphate-reducing bacterial population. Loss of O_2 by diffusion out from the worm's body tissues into the surrounding sediment might create a halo of oxygenated sediment around itself, extending as a pipe or pendant down below the general level of the oxic/anoxic interface in the sediment at large. In this zone CO_2 might still be extracted, i.e. move from sediment to worm, contributing to the carbon biomass of the worm and promoting cementation in the chalk around it (for both processes see above). Additionally, waste products from the worm, including some of the Fe, concentrated by the worm (probably via its tentacular plume) for use in its haemoglobin, might find its way out into the chalk, there reacting with the H_2S diffusing in from the anoxic sediment to produce the iron sulphide observed (Bromley et al. 1975), even when no flint cylinder was subsequently formed. The limiting factor on iron sulphide production at this stage might be the amount of Fe thus lost from the worm's metabolic system.

At the limit of influence of the worm's oxidising effect in the inactive (locally oxidised) zone (the radius of the chalk core is typically 50 to 75 mm), O_2 would react with H_2S to give the conditions considered necessary by Clayton (1982b; see also Clayton and Mortimore 1984) to precipitate the silica that would form the basis for the ultimate generation of flint. Hence would be generated the annulus of silica that gave rise ultimately to the flint cylinders that we call potstones.

3. Inactive (anoxic) sediment zone

At some greater depth, depending on the amount of depression of the oxic/anoxic interface caused by the loss of O_2 from the worm's body, the sediment would be totally anoxic and undisturbed up to its contact with the burrow occupied by the worm. At this point H_2S would be free to diffuse in to fuel the symbiotic chemoautotrophs in the worm's trophosome. CO_2 could also continue to be abstracted (to provide biomass) from the sediment and therefore further cementation of the chalk around the worm burrow could continue until the reduction of porosity restricted the wormward movement of both H_2S and CO_2 to a rate that conferred no further energetic benefit on the worm. Ultimately this balance might determine the deepest useful extent of the worm's penetration into the sediment.

4. Post-mortem effects

It is easy to envisage that the restriction of H_2S supply through reduction of sediment porosity by sediment cementation could eventually lead to withdrawal of the worm from deeper levels in the sediment. (Are the apparent lateral, horizontal branches of the potstone worm burrows evidence of former positions of its bottom end?) The apparent porosity of both the cemented chalk and the flint-replaced chalk at the time of cementation and replacement was about 7 to 80%, suggesting a depth of burial at the time of no more than a fe (possibly less than 10) metres (Clayton and Mortimore 1984; Clayton, in press), so the worm could actually have reached down to suc levels. However, the potstones and their central worm burrows ofte extend vertically through several metres of chalk, representin sediment accumulation over some hundreds of thousands of years. Di the individual worms live for that long, or were the burrows re-occupied by successive generations of worms? The latter seems mor likely. If so worms would ultimately have died in their burrows their bodies would have decayed, and this could have lead to the fina pyritisation (or glauconitisation) of the worm tube lining an adjacent cemented chalk core of the potstones.

CONCLUSIONS

The account above attempts to bring together: (a) our knowledg that the central chalk cores of potstones contain a central, ver elongate worm burrow, (b) our presumption that such worms must hav gained some advantage from extending so far down into the chalk sediment, (c) the recent discovery that deep-sea ecosystems depending entirely on free H_2S for their primary energy, include elongate Pogonophore worms, utilising symbiotic chemoautotrophic bacteria. We speculate that Pogonophore worms in the Chalk Sea could similarly have lived off ("smoked") free H_2S, in this case generated at some depth in the accumulating chalk sediment. Our explanation begs many questions, but at least it provides a new hypothesis, armed with which we can look once again at potstones and associated phenomena in the Chalk, to see if they fit the hypothesis and thereby learn more about conditions on the Chalk Sea floor.

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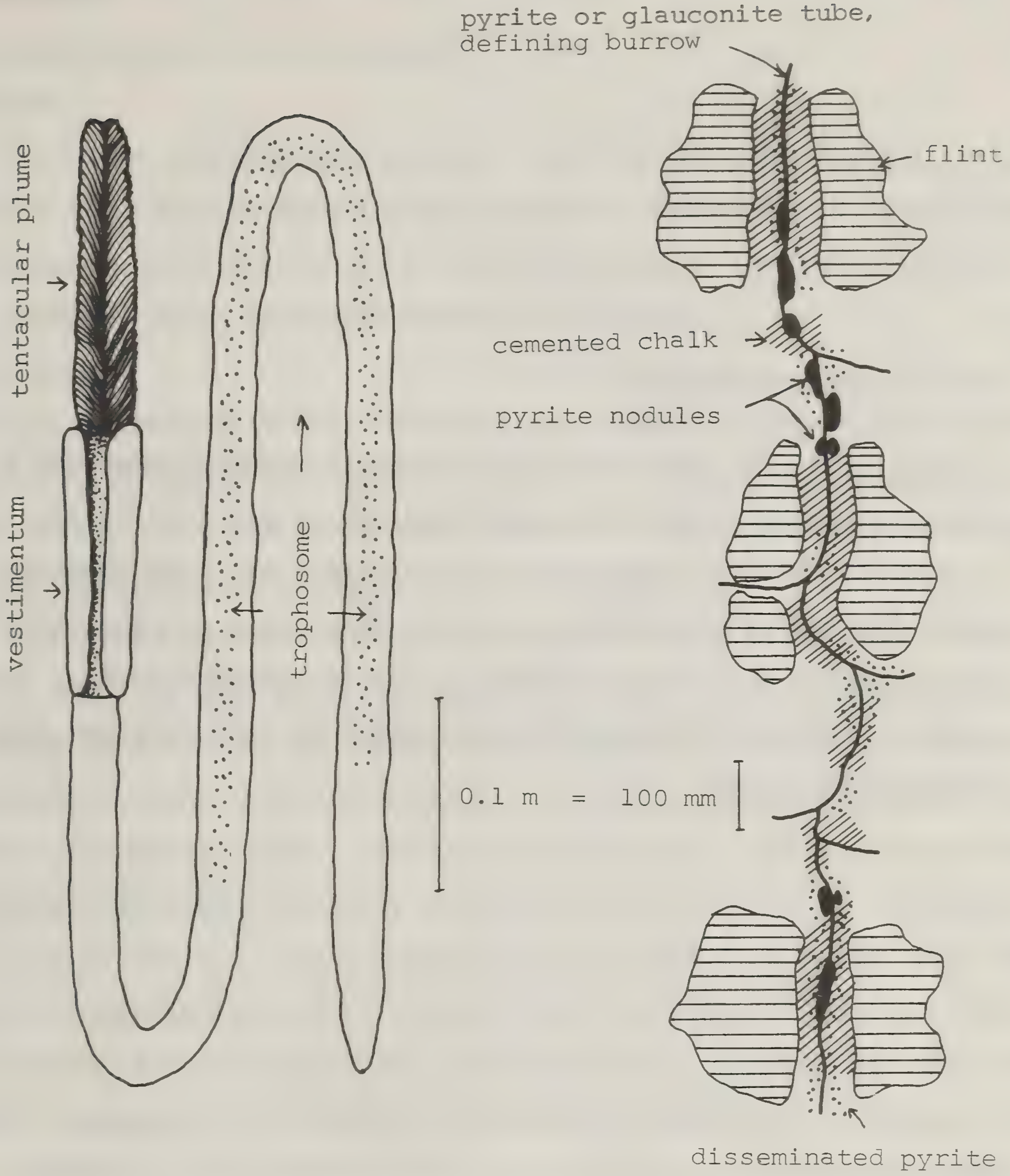
tentacular plume
vestimentum
trophosome
pyrite or glauconite tube, defining burrow
flint
cemented chalk
pyrite nodules
0.1 m = 100 mm
disseminated pyrite

A. *Riftia* worm (after Jones 1981)

B. Potstones, in vertical section (after Bromley et al. 1975)

Fig. 1 Chalk Potstone worms

NOTE ON CHEMOAUTOTROPHY

Autotrophs are organisms that synthesise organic compounds from simple inorganic compounds, using the energy provided by sunlight (photosynthesis - the basis of most life), or, less commonly, using the energy provided by chemical reactions, eg. the oxidation of sulphide. The latter process is called chemosynthesis. Those organisms which utilise energy from chemical reactions are known as chemoautotrophs.

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CONDUCTIVITY MAPPING IN FACIES ANALYSIS OF THE HOLOCENE DEPOSITS OF THE FENLAND

J.A. Zalasiewicz* and R.D. Wilmot+

ABSTRACT

In recent conductivity surveys over the Holocene deposits of the Fenland, silt-filled former tidal channels (roddons) were located, and the tract of silt-dominated terrain that borders the Wash is shown to have progressively less clay content to seaward.

INTRODUCTION

The Fenland (Fig. 1), covering some 3500 sq. km, is the largest expanse of Holocene sediments in Britain. These sediments comprise peat, clay, silt and fine sand which fill a wide depression that deepens north-eastwards towards the Wash embayment.

Two broad facies belts are presented (Fig. 1). The landward facies belt is dominated by peat and clay which is traversed by networks of silt-filled former tidal channels (roddons). Detailed accounts of this facies are given by Godwin (1940, 1978), Gallois (1978), and Seale (1975), and it is depicted on 1:50 000 Geological Sheets of the Wash (145/129), Ely (173) and Peterborough (158) areas. The seaward facies largely comprises silts and fine sands, the "silt lands" of Skertchley (1877), Godwin (1978) and other authors. Little is known in detail about the latter deposits, chiefly because of a general absence of geologically-controlled topographic features, but also because of the limited effectiveness of deep augering methods in these largely arenaceous, waterlogged sediments.

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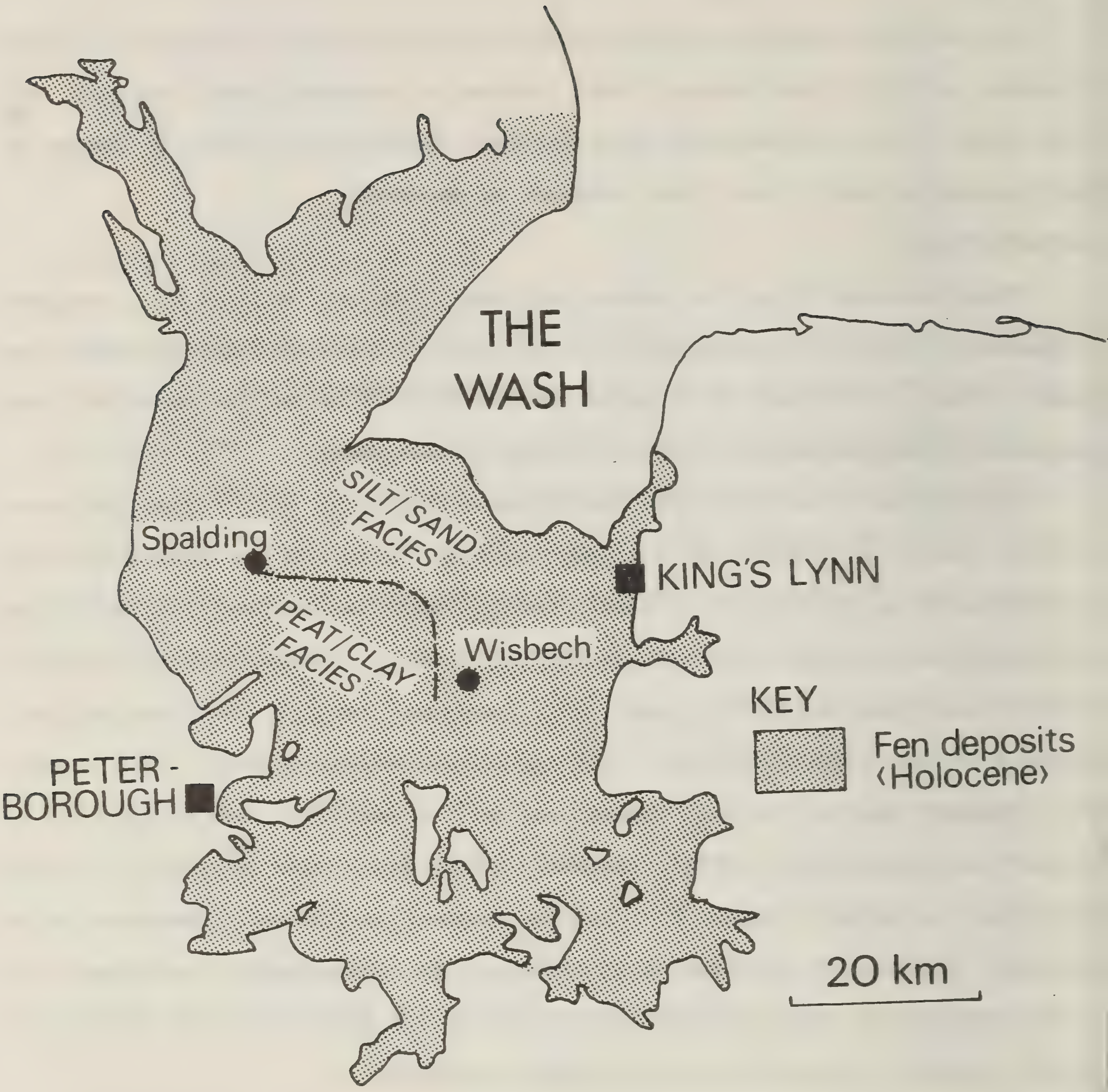
THE WASH
SILT/SAND FACIES
Spalding
PEAT/CLAY FACIES
KING'S LYNN
Wisbech
KEY
Fen deposits ‹Holocene›
PETER-BOROUGH
20 km

Fig. 1 Fenland Holocene facies belts

This paper describes the application of a portable conductivity meter to locating silt-filled former tidal channels and to investigating the structure of the poorly understood silt/fine sand facies belt.

TECHNIQUE

The EM31 Terrain Conductivity Meter manufactured by Geonics Ltd, Ontario, Canada, can be used to differentiate clay-dominated (high conductivity) from sand-dominated (low conductivity) ground. It has an effective depth of penetration of 6-7m and, since it does not require the use of ground electrodes, enables the collection of a large amount of data in a short time. For further details of its operation and its use in other types of terrain see Geonics (1982), Mathers and Zalasiewicz (1984) and Zalasiewicz et al. (1985).

The waterlogged nature of the Fen sediments gives rise to very high conductivities overall, in places near to the effective upper limit of measurement by the EM31 (Geonics 1982). However, the usefulness of the technique can be demonstrated where geological control is present.

APPLICABILITY TO THE DETECTION OF SILT CHANNEL-FILLS

The silt-filled former tidal channels (roddons) of the Fenland vary in width from a few metres to several hundred metres and in depth from c.1m to >10m. At least three near-surface, infilled drainage systems are present, associated with clays that are of salt marsh or lagoonal origin (Godwin 1978).

Conductivity readings were taken across several silt channel fills which traverse clay terrain (Fig. 2a,b); these fills were defined from aerial photographs and by detailed field mapping. The magnitude of the readings shows good correlation with the underlying

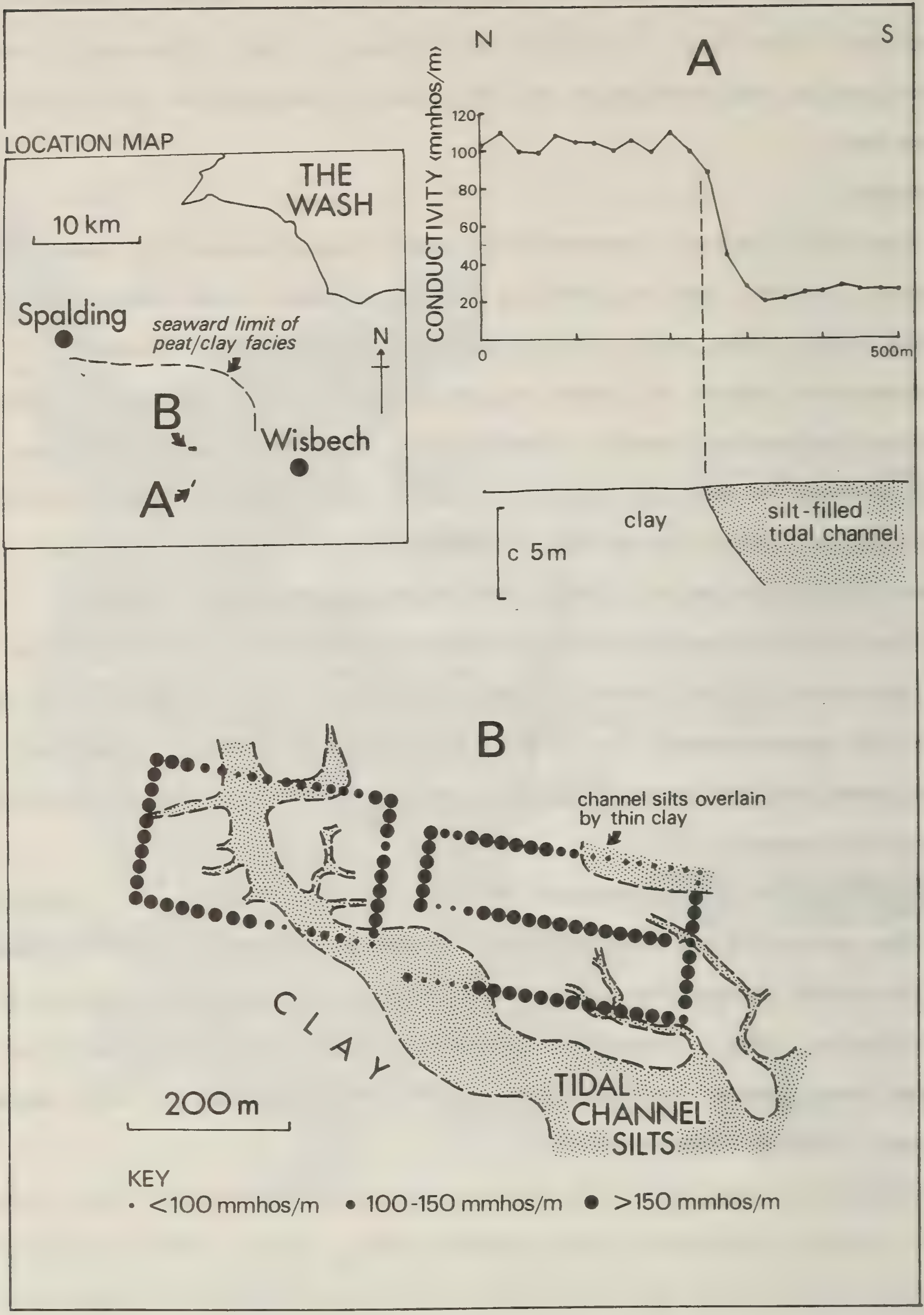
LOCATION MAP
THE WASH
10 km
Spalding
seaward limit of peat/clay facies
N
B
Wisbech
A
N
S
A
CONDUCTIVITY (mmhos/m)
120
100
80
60
40
20
0
500m
clay
silt-filled tidal channel
c 5m
B
channel silts overlain by thin clay
CLAY
TIDAL CHANNEL SILTS
200 m
KEY
• <100 mmhos/m
● 100-150 mmhos/m
● >150 mmhos/m

Fig. 2 Conductivity measurements across silt channel fills

lithology, the major silt fills being traceable as low-conductivity tracts within the high-conductivity clay (Fig. 2a,b); minor silt-filled channels were not detected (Fig. 2b). Conductivity "lows" are associated both with channel silts exposed at surface and with channel silts overlain by thin clay (Fig. 2b); the latter are not visible on aerial photographs and were originally detected by systematic hand-augering.

CONDUCTIVITY ANALYSIS OF THE SILT/SAND FACIES BELT

In the silt/sand-dominated facies lithological changes do not have any detectable surface expression. Calibration along a trial conductivity profile was achieved by augering those sediments that lie above the watertable (Fig. 3a). This shows that the magnitude of the conductivity readings closely reflects the observed thickness of clay-rich sediment.

The conductivity mapping of larger areas (Fig. 3b-d) gave evidence of lithological change across this facies belt. Variable, but generally high-conductivity ground to landward (Fig. 3b) gives way to consistently low-conductivity ground to seaward (Fig. 3d). Thus, preliminary indications are that the upper 6-7m of ground in this facies belt becomes progressively less clayey to seaward. More extensive, systematically calibrated studies on these deposits are likely to be an effective means of determining the distribution of the irregular clay-rich bodies within the silt/sand facies belt.

ACKNOWLEDGEMENTS

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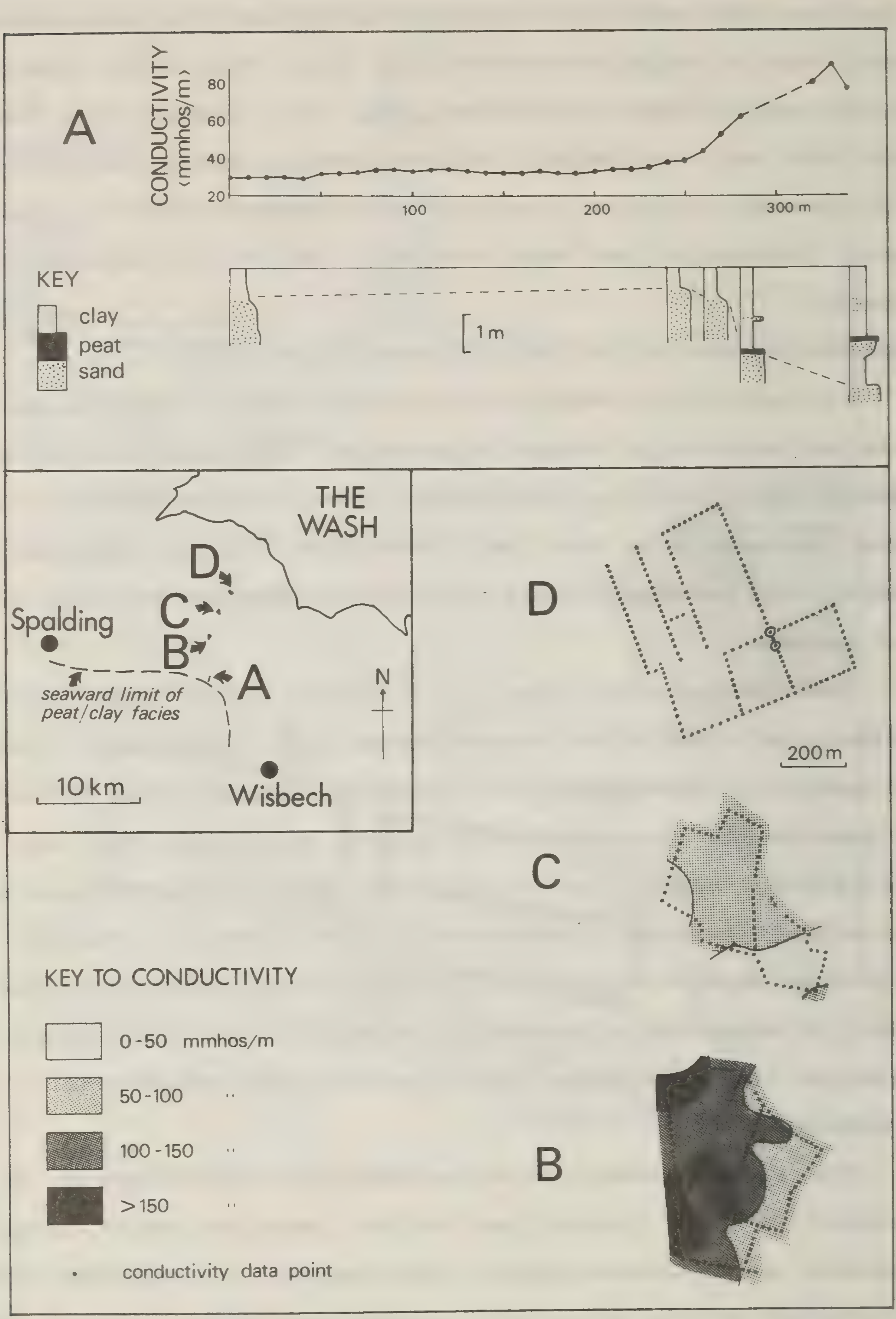

Fig. 3 Conductivity measurements in the silt/sand facies

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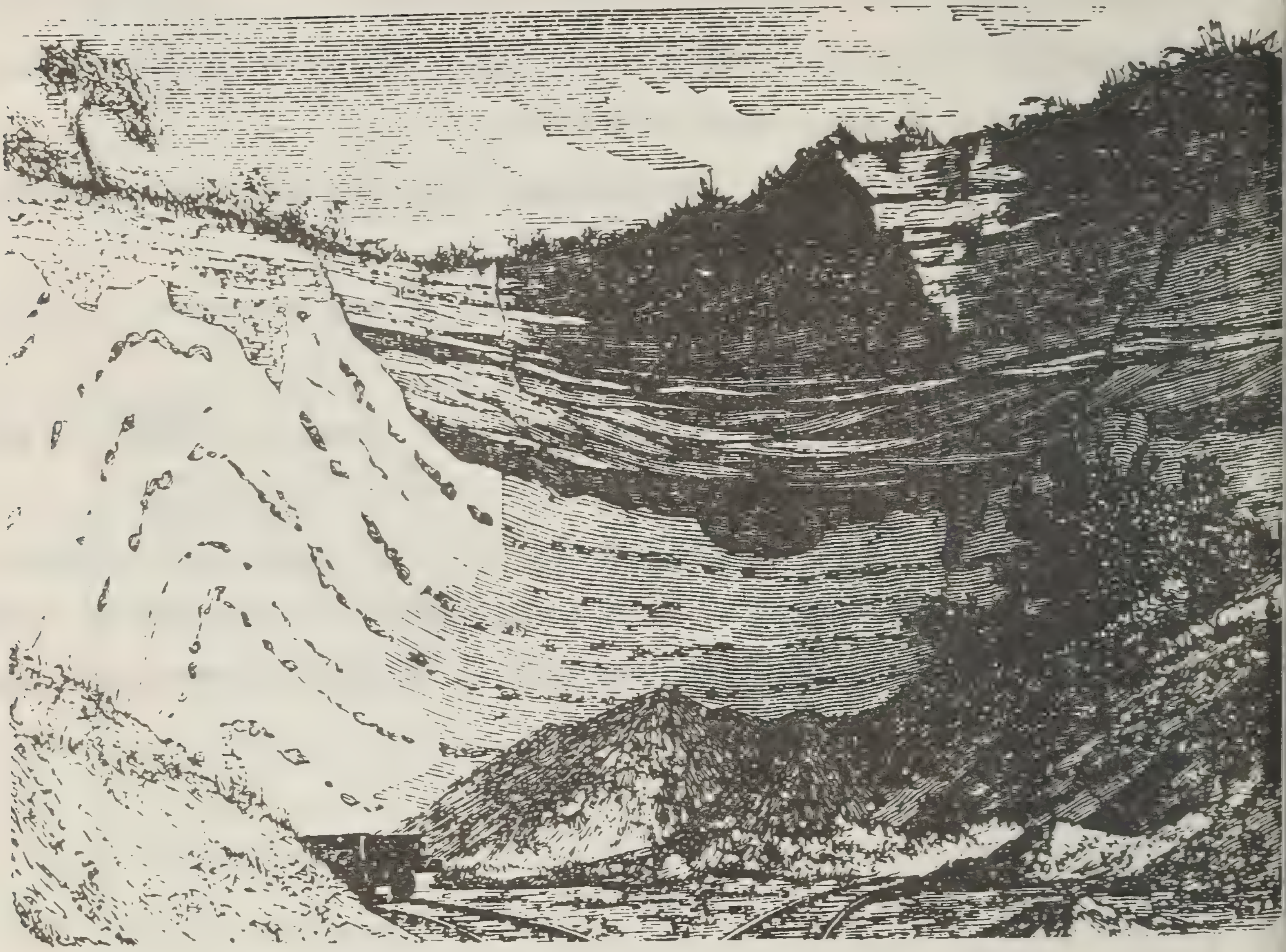

CONTENTS INCLUDE:

Drift behind Sheringham

Highway Engineering in Norfolk

Norfolk sandy beaches

Secretary's report for 1975

(Reproduced as page 96 of Bull. geol. Soc. Norfolk, 36, Sept. 1986)

Bull. geol. Soc. Norfolk, **36**, 97-107 September 1986

THE LAGOONS OF SHINGLE STREET, SUFFOLK: A PILOT STUDY OF THEIR WATER CHARACTERISTICS

J.E. Field and R.E. Randall*

INTRODUCTION : historical background

Shingle Street is part of Bawdsey Parish on the coast of Suffolk, at the mouth of the River Ore. The area is a dynamic accumulation of shingle on a soft substratum of alluvium, Red Crag and London Clay. The shingle is composed of a series of apposition banks enclosing several lagoons of different ages and different distances from the sea (Fig. 1). The coastal lagoons were first described by Cobb (1958) and the history of their origin was detailed by Randall (1973, 1977). The current topographic situation began with violent storms during November 18th - 20th, 1893, when large quantities of shingle were lost from the distal point of Orford Ness and deposited at Shingle Street. Before this time the only lagoons present along the coastline were borrow pits reaching into the London Clay below. These were excavated when the seawall was built earlier in the 19th century. These are shown on the first edition 1:2,500 Ordnance Survey map of 1881 (sheet LXXVII-16) when the whole area was protected by a much longer Orford Ness spit. At this time there were patches of sandy saltings immediately to the east of the seawall and then a shingle foreshore.

The second edition Ordnance Survey map of 1904 (surveyed in 1902, a decade after the storm) shows the northernmost borrow pit reduced in width by 50%, with saltings only to the north. High water mark is virtually unchanged from 1881 but shingle is present much nearer to the borrow pit lagoon and the saltings to the east have disappeared. This lagoon continued to infill until it became ephemeral. On the

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*Girton College, University of Cambridge, CB3 OJG.

1972 3rd edition map it is not shown but shallow water is present in most months still in three separate hollows. This is the site of Cobbs (1958) Lagoon "5" which was surveyed in the present paper. No other lagoons are present on the first or second edition maps.

Immediately to the east of Lagoon 6 there is a 3m high ridge of shingle which is the remains of the distal end of Orford Spit driven landwards by the 1893 storm. The first archival evidence of this lagoon and ridge system is an air photograph taken by R.A.F. on 16.10.1945 (photo 443RS: 106G/U.K./929). However, verbal evidence dates this lagoon to the 1920s and it may in fact be a remnant of the pre-1893 saltings since the substrate on its western shore is sand, and salt marsh plants still grow around it. A deepening and extension southward of this lagoon occurred into the main shingle ridge during World War II gravel excavations and anti-mine device testing.

Lagoon 4 has changed least of the four northern lagoons. Slight infilling occurred at the southern end near "The Beacons" between 1945-1948 but it has remained unchanged since. However, the coastal shingle between Lagoon 4 and the sea has become narrower in recent years. Both Lagoon 4 and Lagoon 7 are part of the original channel of the River Ore which began to be cut off from the estuary in the 1920s, as an elongating North Weir Point allowed protection for northward moving shingle at Shingle Street. Lagoon 4 became isolated in the late 1920s or early 1930s whereas Lagoon 7 was not isolated from the sea arm to the north until 1961 (photos V-AK 93-5, J.K. St. Joseph, Cambridge University collection).

Erosion of the coastal shingle ridge from 1956 onwards and further growth of North Weir Point toward the land encroached onto Lagoon 7 until a sea connection occurred in 1978. This was sealed

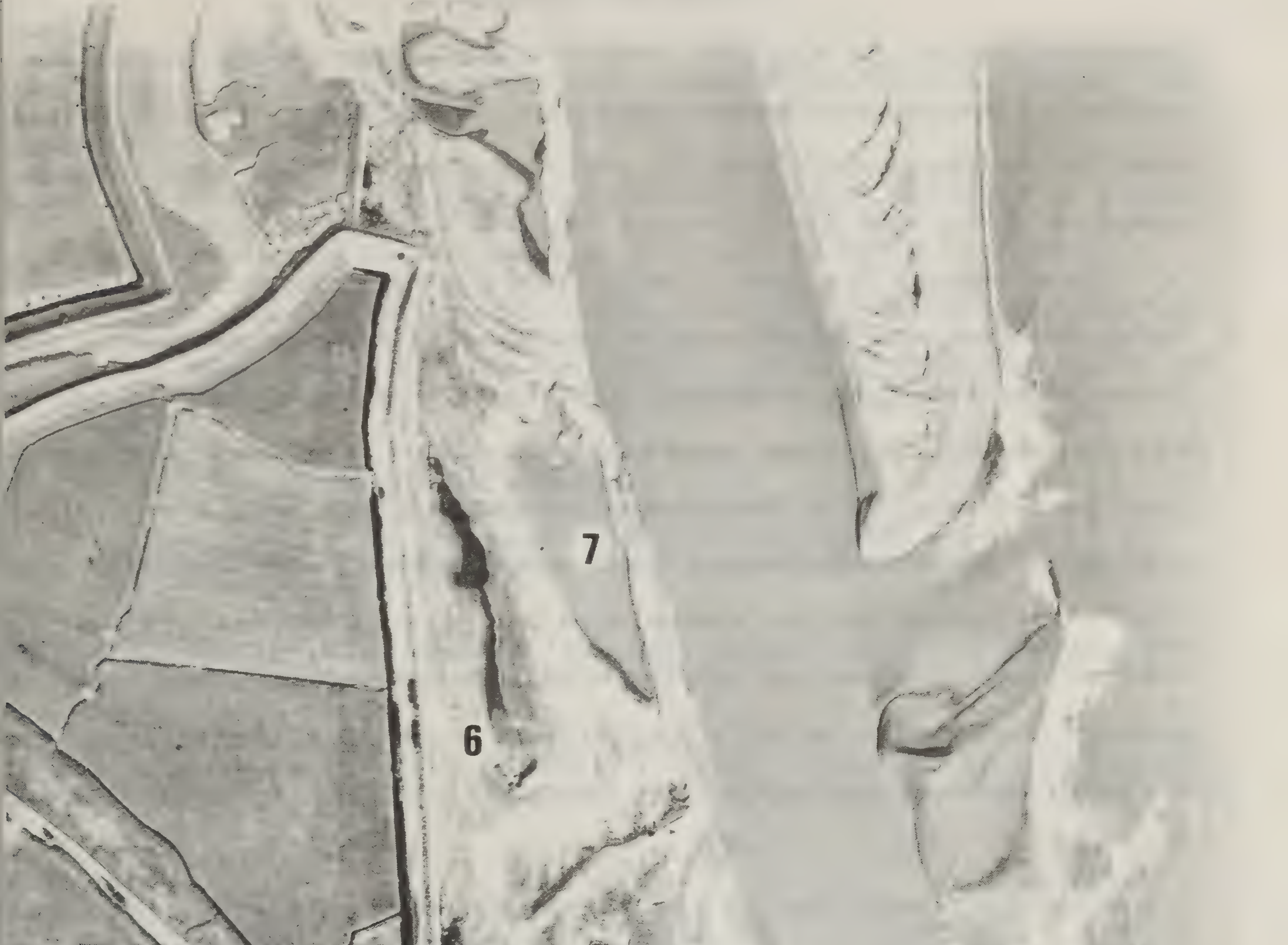

Fig. 1 The lagoon system of Shingle Street (reproduced by permission of the Cambridge University Collection of air photographs; part of RC8-E2 107/4.2.83)

temporarily by the Anglian Water Authority but there have been a series of breaches and closures since. At present Lagoon 7 is less than 50% of its maximum size in 1961 but isolated by a narrow shingle ridge.

Such lagoons are rare in Britain and are infrequently enclosed by shingle elsewhere in the world. Because shingle is permeable such lagoons may receive a variable influx of sea water by percolation, so that although they are spatially isolated they are not hydrographically separate. When Barnes and Heath (1980) made a preliminary survey of these lagoons and their macrofauna it was seen that each lagoon was unique in its assemblages and that additional study of the systems might further an understanding of the lagoonal biology. The present study adds to this data in the hope of stimulating a more thorough research project in the future.

METHODS

The characteristics of the lagoonal waters were studied from 8th - 29th August 1983, and spot-checks were made on 8th December 1982, and during 1983 on 11th January, 15th April, 21st July and 27th November. The main method used was to take conductivity measurements (which give an indication of overall chemical content) using a Pye-Unicam conductivity measuring bridge, but water samples were also taken and analysed for pH and the presence of 3 elements: sodium, potassium and calcium, using an atomic absorption spectro-photometer. Fluctations in water level were observed during the August study period using marked stakes driven into the beds of Lagoons 4, 6 and 7

RESULTS

Table giving conductivity/cubic centimetre readings during the August study period.

Note - 1) Readings for Lagoon 5 cover the period 20th-29th of August only. This is because Lagoon 5 was dry until rainfall caused it to fill during the night of 19th-20 August.

2) Conductivity measurements have been adjusted to give the reading at a standard 25 degrees Centigrade.
The formula used to adjust the conductivities is as follows: $Gt. = G_{25} (1 + a(t - 25))$

Where: Gt. is the conductivity at the temperature of the sample in the field
G_{25} is the conductivity at 25°C
t is the temperature of the sample on site
a is a co-efficient (normally ranging from 1.5 to 2.4%/°C)

It was not possible to measure "a" empirically, so its value has been set at 2.0%/°C for these calculations.

Source of Sample	Mean conductivity	Highest	Lowest in units/cm^3	Range	Standard Deviation	Number of Observations
Mouth of Estuary	49.4	54.5	45.5	9.0	2.53	22
Lagoon 4	46.5	50.0	42.5	7.5	2.17	24
Lagoon 5	34.3	43.0	27.0	16.0	5.22	9
Lagoon 6	50.9	57.0	45.5	11.5	2.45	24
Lagoon 7	50.2	52.5	46.5	6.0	1.55	23

Table giving conductivity/cm^3 readings for spot measurements taken over 12 months (standardised to 25°C)

Date	Conductivity at each site						State of Tide
	Mouth of Estuary	Lagoon 4	Lagoon 5	Lagoon 6	Lagoon 7	Drainage Ditch	
8.12.82	55.0	43.5	32.0	40.0	54.0	-	Rising
11.01.83	48.5	40.0	20.5	44.5	49.0	6.0	Subsiding
15.04.83	56.0	42.5	32.5	39.5	55.0	5.0	High Tide
21.07.83	-	44.0	-	53.0	46.5	-	Rising
27.11.83	48.3	44.5	28.5	45.0	48.5	2.0	Rising

All measurements have been rounded to the nearest 0.5 units

Table showing pH and element concentration measurements

Note - 1) Concentrations are in parts per million

2) In each case, sample "a" was taken on 11.1.83; sample "b" on 29.8.83; and sample "c" on 27.11.83

Source		Calcium	Sodium	Potassium	pH value
Mouth of Estuary	a	354	13280	381	7.10
	b	352	12736	370	7.51
	c	323	9625	406	5.70
Lagoon 4	a	304	9280	329	7.68
	b	336	12416	374	6.69
	c	304	8520	374	5.50
Lagoon 5	a	191	3680	164	7.55
	b	425	10400	383	7.90
	c	224	5120	214	5.40
Lagoon 6	a	316	10048	339	7.80
	b	388	10816	418	7.50
	c	302	8580	362	5.60
Lagoon 7	a	351	13760	380	7.30
	b	347	13760	393	7.51
	c	346	10430	328	5.10
Drainage Ditch	a	108	896	44	7.85
	b	84	512	22	8.49
	c	87	300	30	6.10

Water levels in the August study period

Note: The minimum level observed in the case of each lagoon is designated zero; all other figures are heights above this in centimetres

Lagoon	Range	Average (mean)	Standard Deviation	Number of Observations
4	38.0	20.4	9.0	30
6	54.8	9.4	11.5	29
7	111.7	24.5	27.7	30

CONCLUSIONS

The composition of the waters of the Shingle Street lagoons is both complex and rapidly fluctuating. The potential sources of the water are the sea, the River Ore, precipitation and possibly groundwater; water is lost through evaporation and percolation out through the shingle when the water gradient is reversed.

a) Diurnal changes

Lagoons 4, 6 and 7 showed wide fluctuations in conductivity during August, and similarly large variations in water level due to flushing by estuarine water. In Lagoon 7, the body of water is exchanged almost completely every day as the shingle arm separating it from the sea is thin and quite frequently breached. Lagoon 5 is somewhat different in that during the August study period it appeared to rely totally on rainfall draining into it from surrounding areas of shingle for its supply of water.

In spite of the relatively short distances involved, percolating water may be different both from the water of the estuary and the water of the lagoon into which it is percolating, e.g. on the 27th of August water was observed percolating into Lagoon 4 which had a conductivity of 46.5 units cm^3 as against 54.5 in the estuary and 49.5 in the lagoon. This may show the influence of fresh groundwater. The water of the estuary combines river and sea water in varying proportions, depending on, for example, the height of the tide, or the discharge of the river. This is reflected in a range of 9.0 units/cubic centimetre found in sampling the estuarine waters for conductivity in the summer.

The effect of evaporation on the lagoons was not measurable during the August study period except in the case of Lagoon 5. Here, there was a steady progression from relatively low conductivity immediately after the rain which filled the lagoon, to quite high levels as the volume of water shrank due to rates of evaporation estimated at the time by the Meteorological Office as between 2.9 and 4.4 mm each day. The other lagoons showed no such effect; evaporation was completely masked by water exchange with the estuary, although over a longer time period than was studied the effects might be more important. Evaporation rates from the individual lagoons are likely to vary due to differences in micro-climate.

The extent to which areas were sheltered produced wide variations in windspeeds, air temperatures, and water temperatures in the lagoons themselves. A measurement taken on the 25th of August 1983, for example, showed water temperatures of 19.5°C in the sea; 20°C in Lagoon 4; 23.5°C in Lagoon 5; 25°C in Lagoon 6 (which is very sheltered and relatively shallow); and 22°C in Lagoon 7.

b) Seasonal effects

Spot-checks on water characteristics were carried out over a twelve-month period. Winter conductivity measurements for lagoons 4 and 6 (i.e. those for December 1982 and January, April and November 1983) appeared to be relatively low compared with those obtained in the summer, falling just outside the range of the summer observations in the case of Lagoon 6, but there is insufficient data to test this statistically. If a real difference exits, it is probably accounted for by the increased precipitation of the season combined with a decrease in evaporation and a possible change in the subterranean waters due to changes in the water of the estuary. Higher tides in the estuary may increase the salinity of percolating water in winter, but this could be offset by a higher discharge from the river so that clearly the relatively strength of these two factors is most important, and will vary hourly. The watertable may be higher in winter due to increased precipitation larger discharge and higher tides.

In Lagoon 5, only the January reading fell outside the summer range, but this may be because of the contrast in the character of the lagoon between the seasons. In summer it is ephemeral, filling only after rain and then evaporating away, producing a very large range in conductivity measurements. During the winter, however, it is much deeper and seems to be permanent due presumably either to an increase in the height of the watertable or increased rainfall, or a combination of the two. Winter sodium, potassium and calcium levels are well below those found in nearby Lagoon 6, however, suggesting that the latter lagoon has more contact with water from the estuary. This would be consistent with the relative heights of the two lagoons compared to sea level. Chemical deposits clearly remain on the bed of Lagoon 5 when it is dry, and are re-dissolved after rain, accounting for the much higher chemical content of the lagoon compared with the adjacent drainage ditch.

Lagoon 7 essentially reflects the characteristics of the estuary at all times of the year, owing to its very close proximity to the open water.

SUMMARY

The data presented here constitutes a preliminary survey of the water characteristics of the lagoons.

It is evident however that the water chemistry of the Shingle Street lagoons is highly complex and reflects a fine balance between competing sources of water. Of the four lagoons studied here, two (4 and 6) are quite similar in the way in which they fluctuate, whilst Lagoon 7 mirrors the estuary and Lagoon 5 is distinct in being ephemeral during summer. There is as yet insufficaient evidence to support the extent to which this last lagoon becomes part of the wider circulatory system in winter. The bed of Lagoon 5 is at roughly the same elevation as the surface of the water in Lagoon 4, and with approximately 100 metres horizontally of shingle between them it seems possible that the position of Lagoon 5 is too perched ever to bring it into contact with the watertable of the area except in extraordinary tidal conditions. The surface of the water of Lagoon 6 in August 1983 was almost 2 metres below the bed of Lagoon 5, accounting for the ability of Lagoon 6 to receive percolating water down a 1 in 50 gradient from Lagoon 7 and thus to cut the watertable and maintain a permanent body of water. In contrast to the other lagoons, Lagoon 5 must rely in summer on its sunken position relative to the shingle immediately surrounding it, (which is compacted with soil and vegetation), to promote the runoff of rainwater into the lagoon; the water is held there due to the low peremeability of the deposits on its bed.

The data are too scarce to be able to unravel accurately the mechanism by which fluctuations in the water chemistry of these lagoons are brought about. The small amount of evidence available, however, suggests that further work (including continuous monitoring of water levels and conductivity) would provide interesting insights into the little-known workings of shingle lagoon systems.

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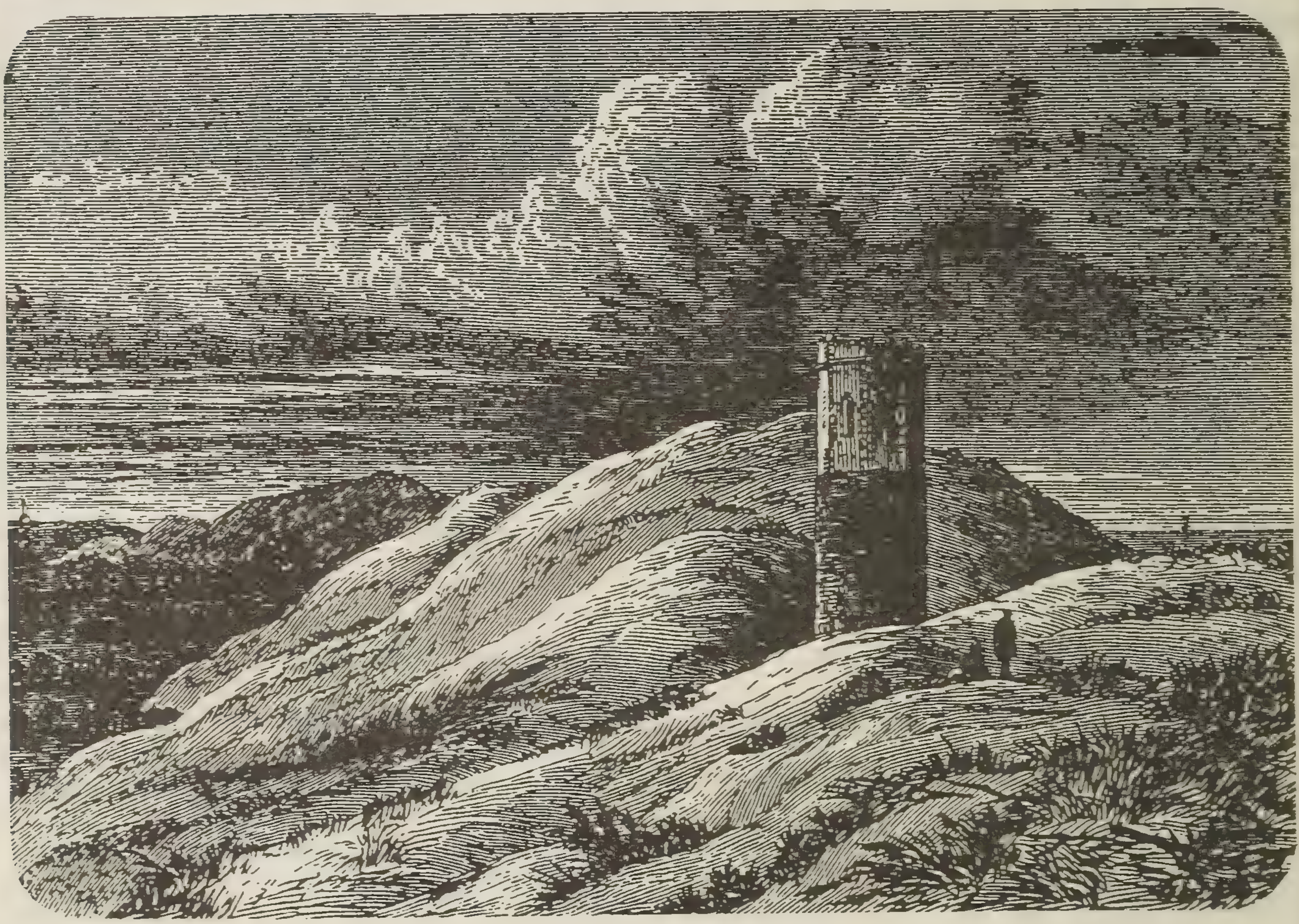
BULLETIN OF THE GEOLOGICAL SOCIETY OF NORFOLK

(FOR ARTICLES ON THE GEOLOGY OF EAST ANGLIA)

No.35

1985



CONTENTS INCLUDE:

Jurassic & Cretaceous of Upware
Chalk Fossils
Coralline Crag Foraminifers
Pleistocene Birds
Catton Pit S.S.S.I.

(Reproduced as page 108 of Bull. geol. Soc. Norfolk, 36, Sept. 1986)

CONTENTS

		Page
Editorial		1
INDEX of the Bulletin of the Geological Society of Norfolk, Nos. 1-35 (1953-1985)		5
Funnell, B.M.	Did the Chalk Potstone worm 'smoke' H_2S?	77
Zalasiewicz, J.A. and Wilmot R.D.	Conductivity mapping in facies analysis of the Holocene deposits of the Fenland	89
Field, J.E. and Randall, R.E.	The lagoons of Shingle Street, Suffolk: a pilot study of their water characteristics	97

The Geological Society of Norfolk exists to promote the study and knowledge of geology, particularly in East Anglia, and holds monthly meetings throughout the year.

Visitors are welcome to attend these meetings and may apply for membership of the Society. For further details write to The Secretary, Geological Society of Norfolk, Castle Museum, Norwich NR1 3JU.

Copies of the Bulletin may be obtained from the Secretary at the address given above; it is issued free to members.

The illustration on the front cover is taken from Figure 286 of Lyell's "Elements of Geology", 1865 (6th Edition), and shows columns of potstones in the Late Campanian Chalk of a quarry on the River Bure near Horstead, Norfolk. The upper part of the section consists of Crag gravels resting on an erosion surface which truncates the potstone columns.

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BULLETIN OF THE GEOLOGICAL SOCIETY OF NORFOLK

(FOR ARTICLES ON THE GEOLOGY OF EAST ANGLIA)

No. 37 1987

CONTENTS INCLUDE:

Giant North Sea Oilfields

Geological Conservation

March gravels of Fenland

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BULLETIN of the GEOLOGICAL SOCIETY of NORFOLK

No. 37 April 1987

Editor: Brian M. Funnell, School of Environmental Sciences,
University of East Anglia, Norwich NR4 7TJ

Assistant Editor: Philip G. Cambridge, 258 Bluebell Road, Norwich
NR4 7LW

EDITORIAL

We are very pleased to re-introduce the tradition of publishing a summary of the Presidential Address. Jeremy Goff delved deep into his considerable experience of oil exploration in the North Sea to bring us an up-to-the-minute, state-of-the-art account of these matters. It is good to know that some of our members have been participating in, and contributing to, the excitement of North Sea exploration over the last few years, and we very much welcome such a well-informed contribution to our Bulletin.

Likewise, we are grateful to Keith Duff for summarising, in permanent form, his talk to us on the Nature Conservancy Council's role in geological conservation. Many of our members participate in such work at a local, volunteer level, and it is good to have such endeavours set in a national perspective.

Richard West has obliged us yet again with new information on the March Gravels and associated marine deposits of Fenland. At the same time he draws attention to the widely different nature of the Fenland-Wash basin in successive interglacial periods.

Finally, having drawn attention to the early issues of the Bulletin, by including them in the Index published in Bulletin No. 36, we can now announce that we are well on the way to producing a Reprint of those early issues. Facsimile reproduction is not possible, because early numbers were produced on duplicating paper, but they have been re-set exactly as they originally appeared - without alteration or embellishment. We hope you will enjoy looking back over 30 years to the early days of the Society. Some of the early numbers make fascinating reading. All being well we expect to issue the Reprint of Bulletin Numbers 1 to 10 later in 1987, and Numbers 11 to 18 in 1988.

INSTRUCTIONS TO AUTHORS

Potential contributors should note that although we prefer manuscripts to be submitted in typewritten copy we will accept neatly handwritten material. It is most helpful if the style of the paper, in terms of capitalisation, underlining, punctuation, etc. is made to conform strictly to those normally used in the Bulletin. All measurements should be given in metric units. The reference list is the author's responsibility and should always be carefully checked.

Illustrations are important. They should be drawn with thin dense black ink lines. Thick lines, close stipple or patches of solid black should be avoided as these tend to spread in the printing process usually employed. Original illustrations should, before, reproduction, be not more than 175 mm by 225 mm. Full use should be made of the first (horizontal) dimension, which corresponds to the width of print on the page, but the second (vertical) dimension is an upper limit only. Half-tone (photographic) plates can also be accepted, provided the originals exhibit adequate contrast, and when their use is warranted by the subject matter.

Authors are reminded that the Bulletin of the Geological Society of Norfolk exists to publish research papers, notes or general articles relevant to the geology of East Anglia as a whole, and does not restrict consideration to articles covering the geology of Norfolk alone.

Bull. geol. Soc. Norfolk, 37, 3-18 April 1987

THE FORMATION OF THE GIANT OIL FIELDS OF THE NORTHERN NORTH SEA

(Presidential Address for 1986, delivered 17 February 1986)

J.C.Goff*

INTRODUCTION

The Northern North Sea Basin contains a Mesozoic rift system buried below thick Upper Cretaceous and Tertiary mudstones and sandstones (Fig. 1). This rift system contains about 10 billion barrels of recoverable light oil and is thus one of the most prolific oil provinces in the world. It is now well explored, with excellent seismic definition of the key unconformity at the base of the Cretaceous section. There is good stratigraphic control from wells on the major structural highs and also in many of the more basinal areas between these highs. Geochemical data has been obtained from thick organic-rich mudstones of Upper Jurassic age which are the most important oil source rocks in the basin. Most of the oil discovered is trapped in Middle Jurassic shallow marine sandstones. The in-place oil volumes trapped in the major fields are fairly accurately defined from analysis of appraisal and development well results.

The Northern North Sea Basin is thus an excellent area in which to study the processes by which giant oil fields are formed. This paper is a summary of the author's research on this topic performed during the last ten years at British Petroleum and the United Kingdom Department of Energy. Two areas have been studied in detail: the East Shetland Basin (Figs. 2 and 3) and part of the East Shetland Platform and Viking Graben (Figs. 4 and 5).

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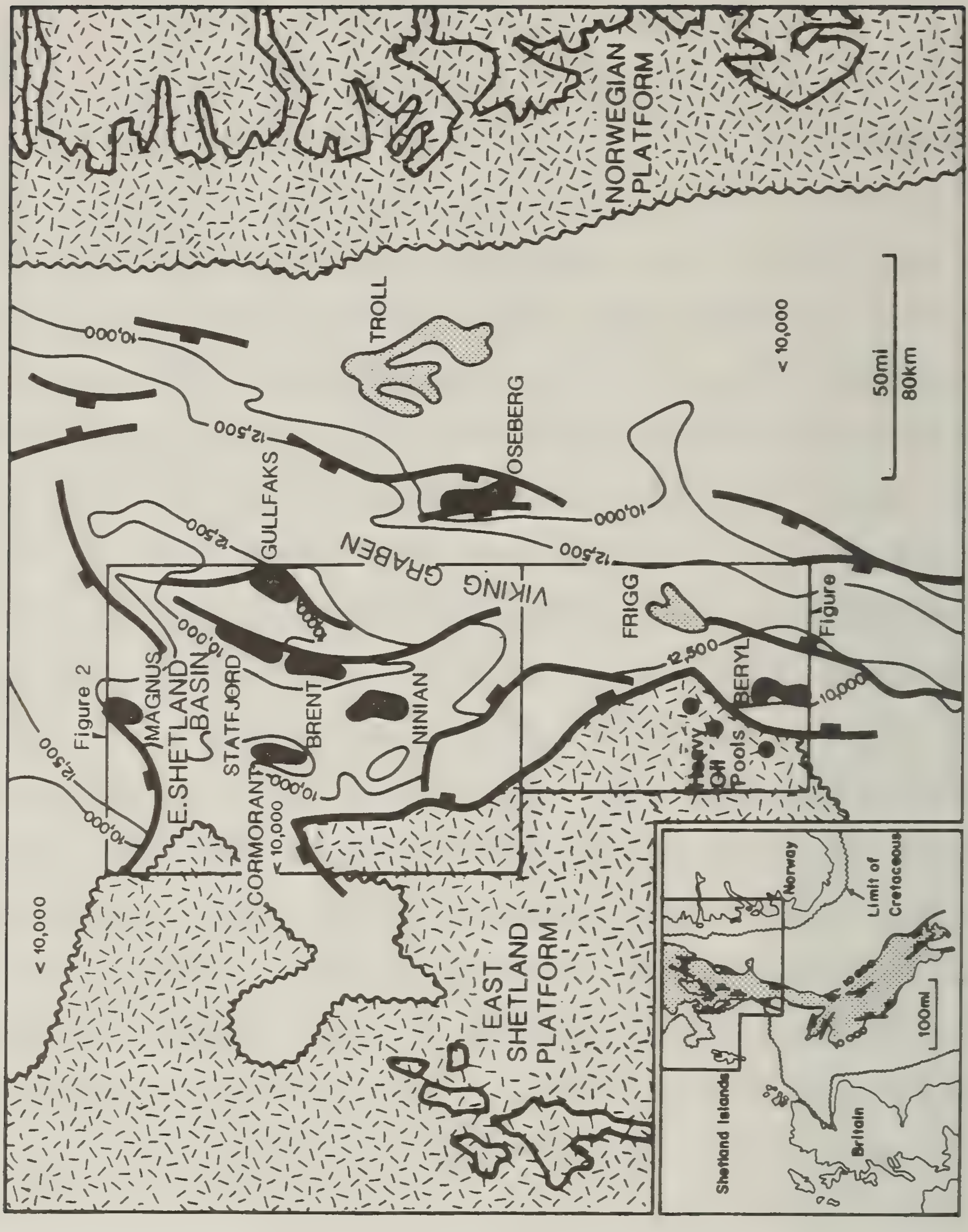

NORWEGIAN PLATFORM
TROLL
< 10,000
50mi
80km
OSEBERG
GULLFAKS
10,000
12,500
VIKING GRABEN
FRIGG
12,500
BERYL
10,000
Figure
Heavy Oil Pools
NINIAN
BRENT
STATFJORD
CORMORANT
< 10,000
MAGNUS
E.SHETLAND BASIN
Figure 2
< 10,000
EAST SHETLAND PLATFORM
Shetland Islands
Britain
Norway
Limit of Cretaceous
100mi

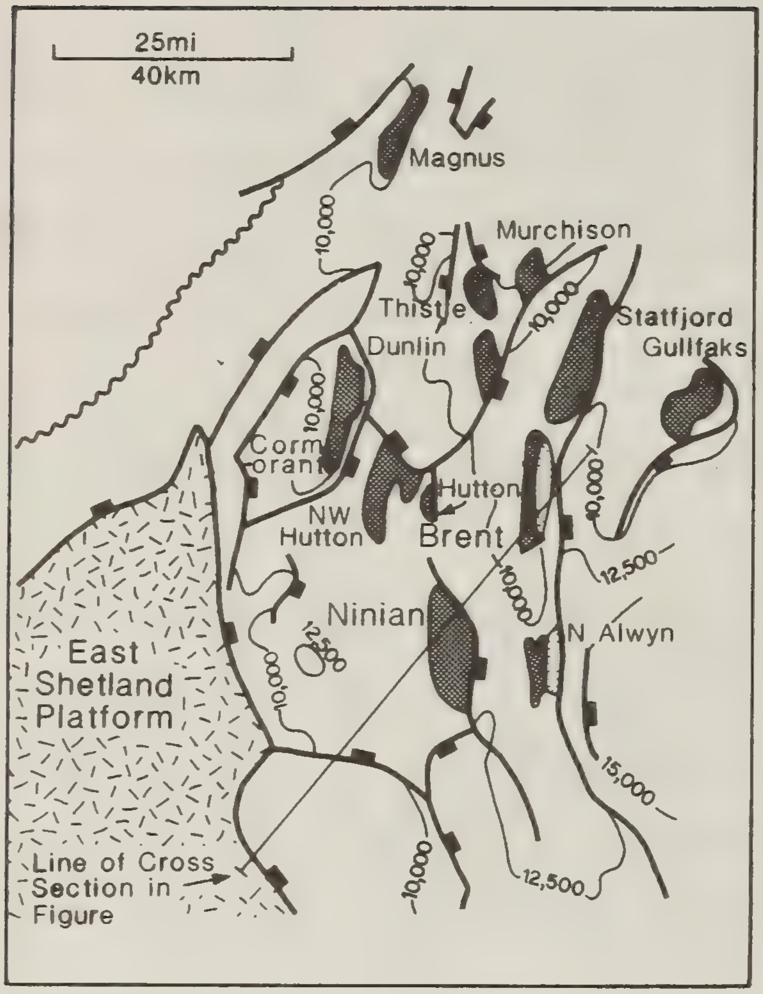
Figure 1 Geological Structure of the Northern North Sea at Base Cretaceous Level

Major Oil Fields indicated by dense stippling, gas fields by light stippling. Inset in bottom left hand corner shows geographic location of the Northern North Sea, boxes show location of the two study areas

FORMATION AND SUBSIDENCE OF THE NORTHERN NORTH SEA BASIN

A fundamental process in the formation of these oil fields is the formation of the sedimentary basin itself, which allowed the accumulation of 8,000-15,000 feet of Jurassic-Tertiary sediments. The progressive accumulation of sediments, together with the flow of heat through the continental crust below the basin, controls the temperature distribution in the oil source rocks. Since the formation of oil is a thermally controlled process, the subsidence history exerts a strong control on the location and timing of oil formation in the basin.

Goff (1983) applied Mackenzie's (1978) model of sedimentary basin formation to the origin of the Viking Graben. The Late Jurassic to Recent subsidence of the Viking Graben is the result of three processes. Firstly the stretching, and consequent thinning of the continental lithosphere during the Late Jurassic rifting, caused an initial fault-controlled subsidence which maintained isostatic equilibrium. This fault-controlled subsidence allowed up to 6000 feet of syn-rift mudstones to accumulate in the axial Viking Graben in Late Jurassic and Early Cretaceous time (Fig. 5). Up to 2000 feet of syn-rift mudstones accumulated along the western fault-controlled edge of the East Shetland Basin (Fig. 3). Secondly a phase of thermal subsidence occurred due to cooling of hot asthenosphere (Upper Mantle) rock below the thinned lithosphere. Up to 5000 feet of Late Cretaceous mudstones were deposited during this phase of thermal subsidence. The thermal subsidence continued at a reduced rate during Tertiary time. The third cause of subsidence is the deposition of sediment itself. The thick Late Cretaceous mudstones and prograding wedges of Tertiary sediment created a major load on the subsiding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40km
Magnus
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Statfjord
Gullfaks
Dunlin
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orant
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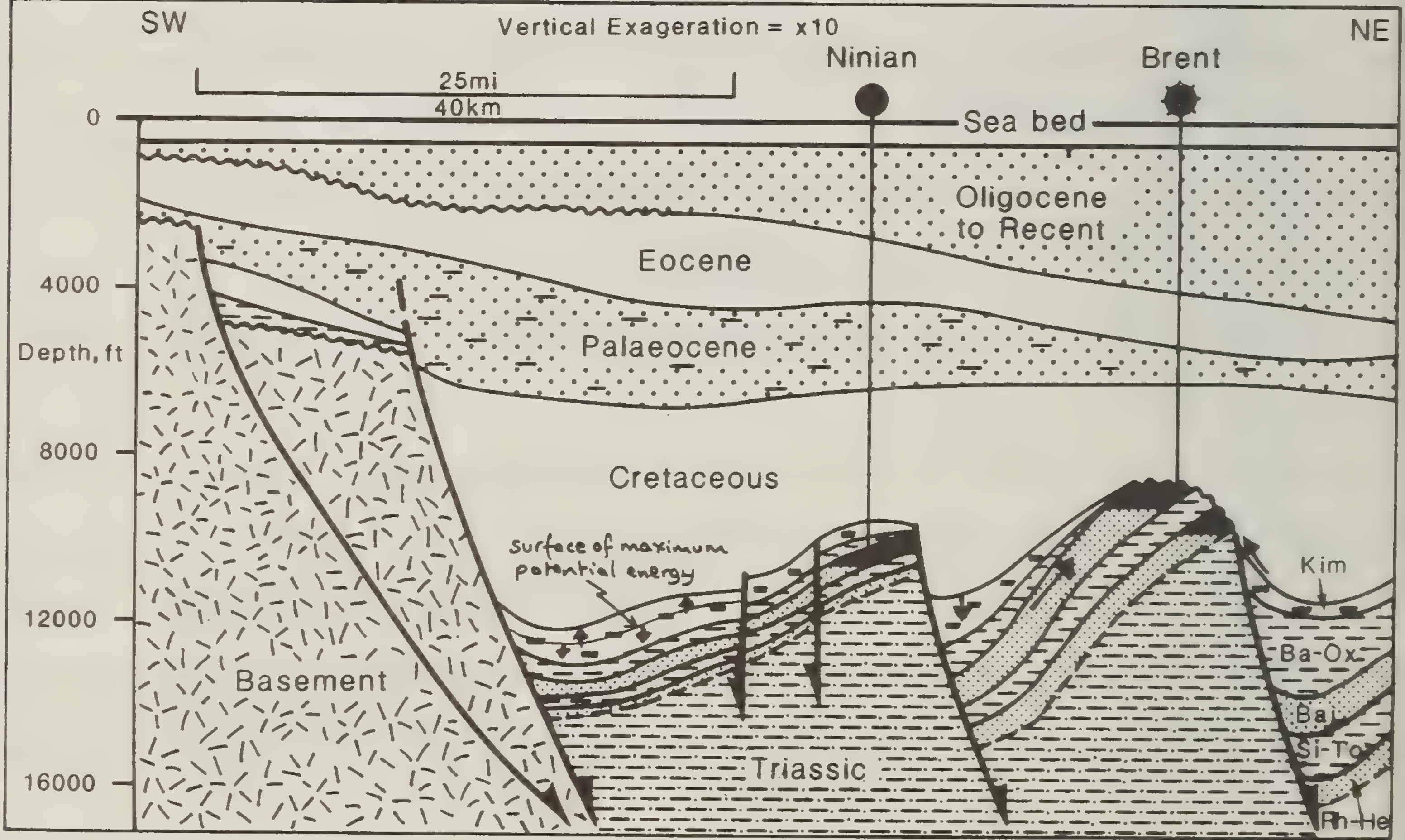
NW
Hutton
Brent
10,000
12,500
Ninian
10,000
12,500
10,000
N Alwyn
East
Shetland
Platform
15,000
Line of Cross
Section in
Figure
10,000
12,500

Figure 2 Base Cretaceous depth structure of the East Shetland Basin

Heavy stippling shows locations of oilfields with recoverable reserves of more than 200 million barrels; light stippling shows gas cap in Brent Field and gas condensate accumulation in North Alwyn Field. Underlying Jurassic source rocks are mature for oil generation below 10,000 feet. Arrows show oil migration into Brent and Ninian Fields.

Figure 3 SW-NE Cross Section through the East Shetland Basin

Key to Jurassic sequences: Kim = 'Kimmeridigian' (main source rock); Ba-Ox = Bathonian-Early Oxfordian; Baj = Bajocian (main reservoir rock); Si-To = Sinemurian-Toarcian; Rh-He = Rhaetian-Hettangian.


SW
Vertical Exageration = x10
NE
Ninian
Brent
25mi
40km
0
Sea bed
Oligocene
to Recent
Eocene
4000
Depth, ft
Palaeocene
8000
Cretaceous
surface of maximum
potential energy
Kim
12000
Ba-Ox
Basement
Baj
Si-To
16000
Triassic
Rh-He

continental crust.

STRATIGRAPHIC FRAMEWORK

Non-marine Triassic sediments comprising thick alluvial fan and fluvial sandstones and mudstones were deposited in rift valleys cut into the underlying Caledonian basement. Marine and deltaic post-rift Early and Middle Jurassic sediments overlie the Triassic section. The Middle Jurassic (Bajocian) sandstones are the most important reservoir rock. They are the product of a northerly prograding, sandy, shoreline/deltaic depositional system. Thick, coarsening-up, micaceous sandstones of the prograding delta front and shoreface are overlain by very porous, permeable, quartzose, sandstones. These quartzose sandstones comprise marine bar, local beach, fluvial and tidal channel sandstones. Overlying delta plain deposits, which accumulated landward of a major marine bar system, comprise lagoonal mudstones, tidal and fluvial channel sandstones and muddy coals. These coals are locally important oil and gas source rocks. The delta plain facies are overlain by transgressive sheet sandstones. The Early Jurassic mudstones which underlie the Middle Jurassic sandstone reservoir form a bottom seal.

The most important period of rifting in Late Jurassic/Earliest Cretaceous time created the tilted fault blocks defined by the Base Cretaceous unconformity. The rifting formed numerous half grabens and grabens which were infilled by organic-rich Late Jurassic mudstones and organic-poor Early Cretaceous mudstones (Fig. 3). Two Late Jurassic sequences have been recognised: Bathonian-Early Oxfordian grey coloured mudstones containing 5-10% by volume organic matter, and dark brown/black Late Oxfordian-Berriasian (including Kimmeridgian) mudstones (equivalent to the Kimmeridge Clay Formation of the onshore

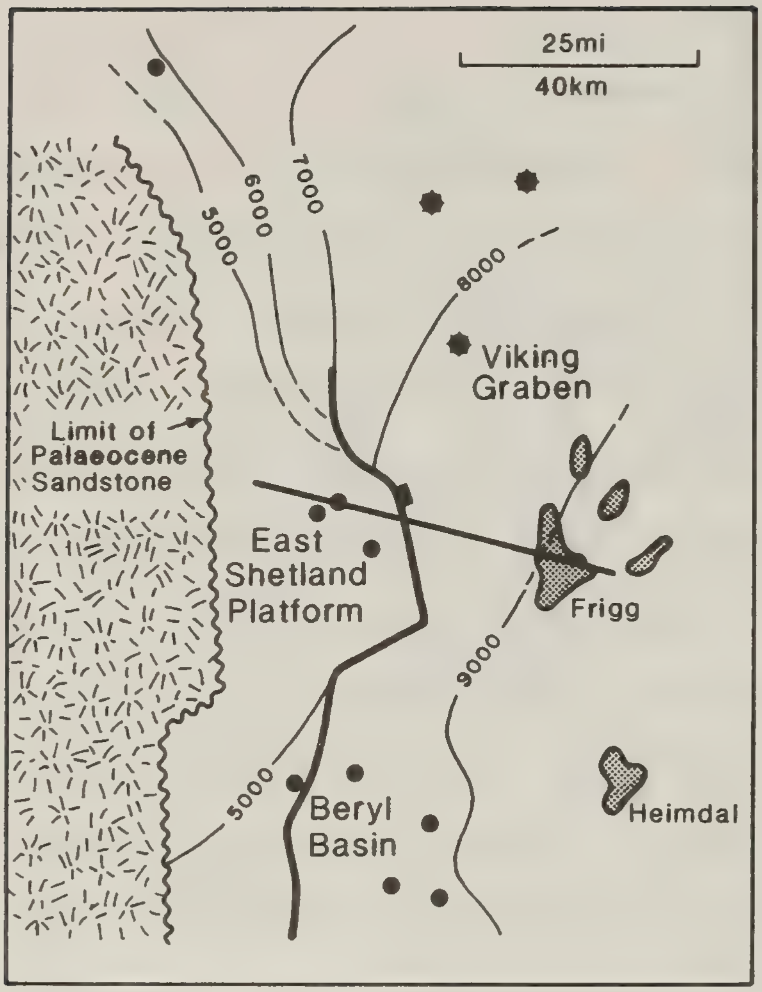
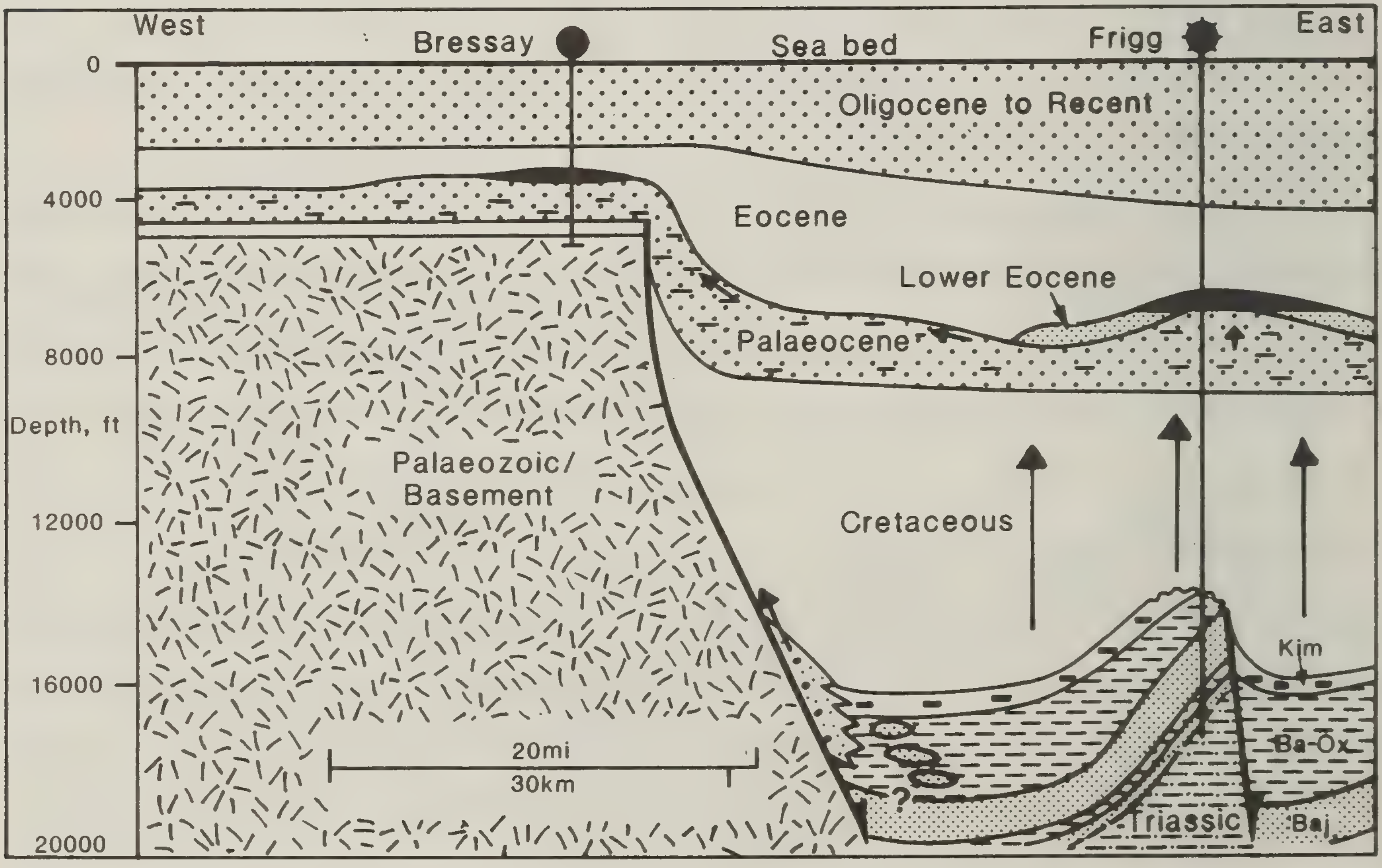

25mi
40km
7000
6000
5000
8000
Viking Graben
Limit of Palaeocene Sandstone
East Shetland Platform
Frigg
9000
5000
Beryl Basin
Heimdal

Figure 4 Base Palaeocene depth structures of part of the East Shetland Platform and Viking Graben

Stippling shows locations of dry gas fields in Lower Eocene and Palaeocene sandstones; these gas fields overlie thin oil columns. Dots show location of heavy oil pools in Lower Tertiary sandstones

Figure 5 W-E cross section through the East Shetland Platform and Viking Graben

Key to Jurassic sequences as for Figure 3. Oil and gas have migrated through up to 6000 ft of Cretaceous mudstones into the Lower Tertiary reservoirs. Arrows show oil migration routes


West
Bressay
Sea bed
Frigg
East
0
4000
8000
Depth, ft
12000
16000
20000
Oligocene to Recent
Eocene
Lower Eocene
Palaeocene
Palaeozoic/ Basement
Cretaceous
20mi
30km
?
Kim
Ba-Ox
Triassic
Baj

UK) which contain on average about 20% by volume organic matter and are the most important source rocks.

Cretaceous mudstones onlap onto the tilted fault blocks at the Base Cretaceous unconformity (Figs. 3 and 5). By Campanian time the Jurassic sandstone reservoirs in the tilted fault block traps were completely sealed by the overlying Late Jurassic and Cretaceous mudstones. During Tertiary time regional subsidence occurred above the Cretaceous depositional basin. In Palaeocene and Early Eocene time submarine fans prograded into a deep water basin. These fans contain important reservoir rocks in the Viking Graben (Early Eocene) and on the East Shetland Platform (Palaeocene). They are sealed by overlying Eocene mudstones (Fig. 5). In Late Oligocene time the basin shallowed and Oligocene-Recent clastic wedges prograded into the basin.

DEPOSITION OF THE KIMMERIDGIAN SOURCE ROCK

The Kimmeridgian organic-rich mudstone is finely laminated and pyritic and was clearly deposited in a strongly reducing environment. The water in the Late Jurassic rifts must have been stratified with dense oxygen-poor bottom waters. Whether this stratification was due to salinity contrasts between the surface and bottom waters (brackish water cap or abnormally saline base) or due solely to temperature differences is not yet known. The anoxic conditions of Kimmeridgian time extended far beyond the Northern North Sea and probably had a large scale tectonic and palaeogeographic control.

The organic matter in the Late Jurassic source rocks in the E. Shetland Basin is derived predominantly from land plants (contrary to the popular belief that it is derived from marine algae). It consists of woody material, bacterially altered wood fragments, abundant spores and pollen, and amorphous material believed to be formed by bacterial alteration of woody tissue. Marine algae are rare. The remains of the bacteria which lived in the organic mud also contribute significantly to the organic matter in the source rock.

THE FORMATION OF OIL

Chemists have simulated oil formation in nature by heating samples of Kimmeridgian source rocks in the laboratory at several hundred degrees Centrigrade under pressure in the presence of water. During these experiments 20 to 30% of the organic matter is converted to oil which is chemically similar to oil now produced from the oil fields. The source rock samples used in these experiments were 'immature' (originally containing only small amounts of soluble bitumen quite unlike crude oil in composition). In nature oil forms at much lower temperatures than those used in laboratory experiments and over much longer periods of time.

Temperature measurements in boreholes made during electrical logging and production testing shows that the temperature increases with depth in the Northern North Sea at an average rate of about 35 degrees Centrigrade per kilometre. An average temperature of 105°C is reached at a burial depth of 10,000 feet. Samples of source rock buried less than 10,000 feet contain only small amounts of soluble bitumen. However samples which have been buried to depths of 10,000 to 12,000 feet contain increasing proportions of bitumen very similar in composition to the medium and heavy fractions of crude oil. Gasoline and kerosene fractions are mostly lost from the source rock samples during collection and preparation for analysis.

The depth range over which the oil is observed to form in the source rock (10,000-12,000 feet) corresponds to a temperatures range of 105-130°C; most of the oil forms over an even narrower range of temperatures (115-130°C). By determining the burial and thermal history of the source rocks Goff (1983) showed that oil was generated in the East Shetland Basin during Eocene to Recent times, i.e. during the last 50 million years. In the deep Viking Graben oil began to form in Late Campanian to Palaeocene time. During Early-Mid Tertiary time the source rocks were heated at an average rate of about 0.5°C/million years. The effective heating rate during Late Tertiary time was probably much lower (of the order of 0.1°C/million years), due to cooling of the surface temperature, and deposition of thick sands which have a significantly higher thermal conductivity than the underlying Tertiary and Cretaceous mudstones.

Source rock samples buried below 12,000 feet contain decreasing amounts of crude oil-like bitumen. This is due to cracking of the heavier fractions of the oil to gas and gasoline at temperatures of 130-170°C. Deeply buried source rocks in the Viking Graben generated gas during Oligocene to Recent time.

EXPULSION AND MIGRATION OF OIL

Geochemical analysis of source rocks has greatly increased the petroleum geologist's understanding of the generation of oil in source rocks, but how does the oil migrate from the source rock through very low permeability mudstones to the reservoir rock? This problem has fascinated geologists since the early days of oil exploration.

High capillary forces are known to oppose the movement of oil through fine water - wet pores in clastic rocks. These capillary forces are several orders of magnitude greater in the fine pores of mudstones than in porous sandstones. Oil is able to move updip in sandstones due to buoyancy, but at oil saturations less than a critical level buoyant movement of oil as a separate phase, even in sandstones, is impossible. These factors have led several petroleum geologists to propose that oil migrated in aqueous solution through mudstones and was then exsolved in sandstone reservoirs due to changes in temperature and water chemistry. However the oil solubilities required to transport the oil now in the Jurassic sandstone reservoirs in the East Shetland Basin are several orders of magnitude greater than those observed in laboratory experiments. Furthermore if an aqueous solubility mechanism was important then selective migration of the more soluble hydrocarbon compounds should occur. This is not observed; oils produced from the reservoirs are chemically very similar to oils extracted from the mature source rocks.

Goff (in press) has suggested that compaction is the main driving force for the expulsion of oil from the Upper Jurassic source rocks. Mudstone porosity data from the East Shetland Basin and Viking Graben shows that compaction continues at great depth even in strongly overpressured sections. Over the depth range of oil generation in the East Shetland Basin (10,000-12,000 feet) water-filled mudstone porosity continues to decrease exponentially from 10 to 5%. During oil generation overburden-supporting kerogen is converted to oil. As oil generation proceeds, and the source rock is buried, overburden stress is transmitted to oil-filled pores in the kerogen. The pressure in these oil-filled pores rises until either the capillary forces in the largest mudstone pores are exceeded and the oil is injected into them, or until the rock microfractures. Generated oil is thus concentrated in the most coarsely porous laminae in the source rock and in microfractures. Progressive compaction of the fine oil-filled porosity in the source rock will continually charge the most coarsely porous laminae with oil.

By making the simplifying assumption that the compaction forces act similarly on both the water- and oil-filled pores, and from knowledge of how oil generation varies with depth it is possible to calculate the volumes of oil expelled from a source rock during compaction. The oil explusion efficiency (defined as the percentage of generated oil that is expelled) is estimated at 20% during oil generation (at 10,000-12,000 feet) increasing to nearly 50% at 14,000 feet. Volume increases due to generation of oil and gas from kerogen are an additional cause of overpressuring in the source rock which could cause petroleum expulsion. However the volume increases are probably only significant for gas generation which occurs after the formation of oil.

Oil expulsion efficiencies for mature oil source rocks can be calculated from geochemical data by making the assumption that the original oil-generating potential of a mature sample is equivalent to the potential of an immature sample. The petroleum yield of mature source rocks decreases with maturity due to expulsion of some of the generated oil. The petroleum yield of the Kimmeridgian source rocks decreases from an average value of 320 milligrams of petroleum per gram of Organic Carbon at the beginning of oil generation (10,000 feet) to about 250 milligrams of petroleum per gram of Organic Carbon at the end of oil generation at 12,000 feet. This decrease in petroleum yield is consistent with an expulsion efficiency of 20% predicted by the compaction model of oil expulsion after allowing for leakage of volatile hydrocarbons from the samples. At higher maturity levels corresponding to gas generation, the petroleum yield decreases rapidly with depth.

MIGRATION AND TRAPPING OF OIL IN RESERVOIR ROCKS

The final stages in the formation of the oil fields are the migration of oil from the source rocks to the reservoirs, the migration of oil in the reservoirs, and the pooling of oil in the traps. To understand the migration of oil quantitatively it is necesssary to estimate the fluid potential energy gradients in the compacting source rocks (since fluids migrate from high potential energy or excess pressure to regions of lower potential energy). Once the oil is expelled into the reservoirs, the geological structure controls the buoyant movement of oil towards the traps.

In overpressured source rocks the higher the porosity (Fluid Content) at a given depth, the higher the excess pressure. Measurement of the sonic transit time of thick Kimmeridgian source rocks in the half grabens indicates that the highest excess pressure in the source rocks occurs 800 to 1000 feet above the top of the Middle Jurassic sandstones (Fig. 3). The geometric surface of maximum excess pressure (= maximum potential energy) in the compacting source rocks defines the directions of oil migration. Below this surface the oil migrates downwards towards the underlying sandstones.

Study of the pressure regime in the overpressured Jurassic sandstones place important constraints on the volume of source rock drained by individual fault blocks. Reservoir pressure and fault pattern data indicate there are about ten different aquifer systems in the Middle Jurassic sandstones in the East Shetland Basin. Each system has a characteristic amount of overpressure ranging from a few hundred to several thousand pounds per square inch. The systems are isolated from one another by sealing faults which throw the sandstone reservoirs against mudstone units (Fig. 3). Water and petroleum is expelled into the sandstones from overlying mature source rocks in downdip positions. At structurally higher levels in the fault blocks the excess pressure in the overpressured reservoirs probably exceeds the excess pressure in the overlying mudstones. Water is expelled out of the reservoirs here, but the oil is trapped in the sandstones due to high capillary forces in the mudstone caprocks which overlie the oil fields.

The geological structure of the top reservoir surface within each reservoir pressure system defines the oil migration routes within the reservoir. It is thus possible to estimate the drainage areas of groups of oil fields in each pressure system. The volume of source rock drained by each group of oil fields can be estimated from the size of the drainage area, the thickness of the source rock, and the extent of downward flow from the compacting source rocks. The amount of oil expelled from each source rock drainage volume can then be estimated from the potential oil yield of the source rock, the extent of oil generation, and the weighted average oil expulsion efficiency. Comparison of the calculated oil charges of groups of oil fields with the known in-place petroleum in the fields shows that the compaction model of oil expulsion predicts the in-place petroleum volumes to within an accuracy of 20%. The calculated oil charges are about 20% greater than the in-place volumes in the fields. This is probably due to loss of oil along migration paths and to the presence of undiscovered oil fields in the drainage areas.

Goff

VERTICAL MIGRATION OF OIL INTO TERTIARY RESERVOIRS INTHE VIKING GRABEN

In the second study area on the East Shetland Platform and in the Viking Graben, large volumes of heavy oil and gas are trapped in Palaeocene and Lower Eocene submarine fan sandstones in large, low relief domal traps (Figs. 4 and 5). In this part of the Viking Graben oil generated in the Kimmeridgian source rocks has migrated through up to 6000 feet of overlying Cretaceous mudstones. Lower Tertiary sandstones in the Viking Graben contain mainly gas; these reservoirs lie above very deepy buried Jurassic source rocks in which intense gas generation has occurred.

The traps on the East Shetland Platform contain mainly heavy oil. These traps lie above, and to the west of, Jurassic source rocks which are mature for oil generation. In addition gas has probably displaced large volumes of oil out of the Lower Tertiary reservoirs in the Viking Graben up onto the East Shetland Platform.

The vertical migration of oil and gas through the thick overpressured Cretaceous mudstones is certainly a very slow and discontinuous process; the excess pressure in the Cretaceous mudstones increases from zero at the top of the overpressured zone to 7500 pounds per square inch at a depth of 17,000 feet. The high degree of compaction disequilibrium in these overpressured mudstones indicates very low permeabilities and hence very low fluid flow rates. Several migration processes probably occur in the Cretaceous mudstones of the Viking Graben (Goff, in press) including methane diffusion, transport of methane in aqueous solution and subsequent exsolution in the Tertiary sandstones, and migration of oil through interconnected pores and microfractures.

The heavy nature of the oil found in the Tertiary reservoirs is probably due to solution of light oil fractions in gas trapped in the Cretaceous mudstones, and also to alteration of the oil after it had been expelled into the Tertiary sandstones. During Oligocene and Miocene time sandy shoreline/deltaic depositional systems prograded into the basin. Fresh water or sea water may have flowed down from these shallow sandstone reservoirs into underlying Lower Tertiary sandstones. Bacteria in ground waters, which can survive to temperatures of 60°C, are known to attack the lighter fractions of crude oil preferentially, transforming originally light oils into heavy oils. Chemists maintain that the heavy oils of the North Sea have been altered by bacteria in this way but the geological conditions under which bacteria were transported into the Lower Tertiary reservoirs deserve further study.

APPLICATION

Integrated studies of petroleum geology and geochemistry together with studies of the physical principles controlling the movement of fluids in sedimentary basins are becoming increasingly important in oil and gas exploration. They can be used to reduce exploration risk in frontier regions by highgrading those parts of the basin where petroleum has been generated and those areas towards which it is likely to have migrated. A further challenge is to use our increased understanding of how oil fields are formed to seek out more subtle oil and gas accumulations in sedimentary basins which have already been well explored. The Northern North Sea has proved a particularly useful testing ground for models of oil and gas generation, expulsion and migration. This is because of the, perhaps, unique nature of the geology and the extensive data base available which allows the source rock kitchens, where the oil and gas has formed, to be studied in great detail.

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GEOLOGICAL CONSERVATION IN BRITAIN

Keith L. Duff*

(Editor's Note: This article is a summary, by Dr. Keith Duff, of his lecture to the Geological Society of Norfolk given at its meeting in Norwich on 15 September 1986. We are very grateful to Dr. Duff for providing this permanent record of his remarks. Please note that the abbreviation NCC refers throughout to the Nature Conservancy Council, not Norfolk County Council!)

In spite of the increasingly sophisticated "black boxes" which are becoming widespread in geological studies, geology remains essentially a field science, and is likely to stay that way. Because of this, and due in no small part to the increased pressure of development and "environmental improvement", the conservation of geological and geomorphological sites is growing in importance. The fundamental aim of earth science conservation is to ensure that the key sites for research, education and training remain available in the future, and this has been recognised by Government since the 1940's. To act as a national agency for nature conservation, including geology and geomorphology, the Nature Conservancy was established by Royal Charter in 1949 and has grown in size and effectiveness since then. In 1973 it was reconstituted as the Nature Conservancy Council, and is now financed through grant-in-aid from the Department of the Environment. The history of geological conservation goes back further, however, with the first recorded activities of this sort having taken place nearly 100 years ago in Glasgow, with the conservation of the group of in situ fossilised Carboniferous trees known as the "Fossil Grove" inside a wonderfully ornate building in Victoria Park.

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The NCC protects geological sites principally through the notification of Sites of Special Scientific Interest (SSSIs) and National Nature Reserves (NNRs). This is done through powers vested in NCC as a result of a number of pieces of legislation, the main one being the Wildlife and Countryside Act of 1981. The general position is that NNRs are owned, leased or managed by the NCC principally for their conservation interest, whilst SSSIs remain in private owner-ship but are protected through the planning system and by the "Potentially Damaging Operations" (PDOs) procedure. Most geological sites receive adequate safeguard through SSSI designation, with the result that only about 15 of the 214 NNRs are of special geological importance. On the other hand, about 2000 of the 6000 SSSIs which exist are of geological or geomorphological importance. Under the Planning Laws, local planning authorities are obliged to consult NCC whenever a planning application for an area designated as an SSSI is made, and are obliged to take NCC's comments into account when determining the application. This system generally works well, and often results in the imposition of planning conditions designed to protect features of interest; this worked well in the conservation of Catton Chalk Pit in Norwich. In addition to the planning safeguards, all owners and occupiers of SSSIs are notified of a list of operations, any of which, if carried out, could damage the scientific interest of the site. They are required to consult NCC before undertaking any notified PDO and if NCC does not agree to it there are provisions for compensation to be paid for loss of profits in certain circumstances. These safeguards apply solely to operations not requiring planning permission, such as agricultural improvements or forestry, and provide an effective safety net for previously difficult problems.

Geological Conservation in Britain

The coverage of geological SSSIs has recently been revised as a result of the Geological Conservation Review (GCR), a nationwide re-assessment of the key geological and geomorphological sites in Britain. This has been undertaken on a national basis by acknowledged experts in the various parts of the geological column, and will be (in effect) the "Domesday Book" for geological conservation into the twenty-first century. The selection of sites for the GCR has virtually been completed, and publication is now being planned. It is anticipated that publication will be spread over a period of about five years as a series of some 50 paperback volumes, each relating to specific parts of the geological column or to particular types of feature.

The range of localities and features safeguarded is very wide, covering the whole breadth of geology and geomorphology, and including stratigraphy, palaeontology, igneous sites, metamorphic and structural sites, mineralogy, geomorphology and Quaternary geology. The benefits deriving from their conservation can be argued to have pure scientific benefits, training and economic benefits, and a "heritage" benefit. The scientific justification is founded on the fact that it is important to be able to re-examine previously-studied sites in the light of new techniques or theories which have been developed, and also on the fact that many British sites are regularly and heavily used for research in its own right. The training and economic benefits derive from the scientific importance of localities, and are due to the need for long-term safeguard of key sites for training geologists of the future, so that the nation's supply of suitably trained geologists, capable of locating new reserves of the raw materials upon which our technologically-dependent society is founded, can be assured. Many British coastal sites are also of importance as on-shore comparative sections against which rock sequences observed in boreholes in the North Sea, English Channel or Western Approaches can be calibrated. The third strand relates to "heritage" and derives from the fact that there are so many classic and historically important geological sites in Britain, due largely to much of the early development of geology having occurred in Britain in the nineteenth century. Many of Britain's classic fossil or mineral sites are world famous, such as the Jurassic reptile horizons of the Lias and the Oxford Clay, whilst the oldest known human remains in Europe were discovered in terrace gravels of an earlier course of the Thames at Swanscombe in Kent. Closer to home, the Chalk rafts in the till cliffs of Sidestrand, Overstrand and Trimingham, and the glacio-tectonic features associated with them, are unsurpassed anywhere in Europe, and form a valuable part of our natural heritage.

Geological sites are subject to a variety of threats, and geological conservation is heavily involved in resolving the problems which arise. The two main problem areas relate to development proposals and to the problems caused by geologists themselves. Development proposals can be grouped into a number of categories. Certain activities are actually beneficial to geology, especially quarrying and mineral extraction, which allow the study of rock-masses in three-dimensions. However, this generalisation does not apply to geomorphological sites, which are usually restricted in extent, and where quarrying can significantly damage or even destroy the features of interest. The biggest difficulties in this area arise from proposals to quarry fluvio-glacial sands and gravels, especially from kame or esker systems, and conflict between conservationists and mineral operators may often occur in such situations. Other types of development are usually compatible with geological conservation, such as building residential or industrial premises on the floors of disused quarries. As long as the rockfaces are safeguarded, such activities are usually relatively harmless. Coast defence works and refuse disposal operations are generally incompatible with geological conservation, since they tend to result in the loss of exposures which previously existed. It is in areas such as this that the largest, most intractable, and most emotive conservation problems arise. Much of the Norfolk coast, even the undeveloped parts, is now defended by wooden revetment-type coast protection works, which have resulted in loss of geological exposure, except in areas such as West Runton where a modification to the design of the defences seems to have allowed sufficient marine scour to maintain usable exposures of the Quaternary sequence. Similar problems, not generally resolved so well, occur along much of the south and east coasts of England, between Lyme Regis and Scarborough. The use of disused quarries for waste disposal is equally problematic, since it is very difficult to combine waste disposal and geological conservation, unless all parties believe deeply in the need to co-operate closely. Unfortunately, co-operation of this sort is rare, although one or two good examples do exist, such as at Tolcis Quarry in Devon and at Fosse Cross Quarry in Gloucestershire.

The more difficult conservation problems derive from geologists themselves, either by overuse or misuse of sites. Overuse can give rise to many different problems, ranging from denial of access by landowners who have grown tired of continual trespass, to an inability to study horizons such as the Ludlow Bone Bed because the outcrop has been dug away so much that it is now difficult to reach. The common factors linking these problems is the cumulative impact of visitors. Whilst each visitor may hammer off or remove only a few pounds of rock, the annual result of this being done by several thousand visitors is of a completely different magnitude, and can cause serious problems. It is all too easy to overlook this when visiting an inland site which is not being eroded by the sea or by quarrying operations, and where cumulative effects become apparent much more quickly.

A smaller number of sites can be damaged by misuse, for example by removal of key features such as lenticular fossil horizons, rock structures or sedimentary features as curios. Once collected, and removed from their natural geological context without proper documentation, their value as scientific objects disappears almost completely. Similar problems apply to vertebrate fossil sites, although it is not clear how much of a problem this actually is. Certainly, a good deal of data is lost by not collecting, recording and curating fragmentary specimens and observations, but it seems likely that many vertebrate palaeontology sites are actually quite extensive, and so there remains a possibility of collecting more data in the future. However, this is not the case with natural limestone pavements such as those which occur in the north Pennines, and which have been heavily damaged by removal of stone for use in the rockery trade. The resource of limestone pavement, which is of considerable geomorphological value, is severely restricted and as a result of this extraction of limestone pavement has now become a special control area under the Wildlife and Countryside Act.

To counter all of these potential losses of geological outcrop, NCC has over the past 10 years become more and more involved in "positive" conservation, mainly through the re-excavation of old quarries and cuttings which had become obscured by vegetation and talus. By using earth moving machinery hired from contractors it is possible to recreate lost exposures very easily and quickly, and this element of the NCC's work is one of the most rewarding. It is now generally combined with our "diversionary trail guide" philosophy, whereby a series of alternative sites to attract educational use away from vulnerable over-used sites of importance for research are cleaned and then described in a new geological guidebook. This was the background to the successful publication "New Sites for Old : A students guide to the geology of the east Mendips", which was published in 1985. This describes 39 specially selected geological and geomorphological sites in the east Mendips, and will hopefully act as a model for future similar guides in other heavily used areas.

The "adoption" of geological sites by local geological societies, schools or colleges is an area in which a good deal of progress can be made. The aim is to arrange for a local group to informally adopt localities cleared by NCC, and to keep them reasonably clear of vegetation and talus so that their educational value remains high. The Geological Society of Norfolk has led the way in this area through their activities at Catton Chalk Pit, and a number of comparable schemes have since been initiated elsewhere. This growth of involvement between NCC and the voluntary geological conservation movement offers great potential for the spread of the conservation ethic to more geologists and owners, and can only be of benefit to geology.

Geological conservation has come a long way since 1949 but still has far to go. In order to spread the message more widely it is vital that all geologists, amateur and professional, work together in an attempt to safeguard as much as possible of Britain's geological and geomorphological heritage. Inextricably linked with this is a need to bring geology more into prominence in society generally, so that the role of geology and the geologist is more widely appreciated. In this, the local geological societies can play a fundamental role, and through its actions so far the Geological Society of Norfolk has shown itself well able to accept and excel at this new challenge.

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Further details of NCC Publications may be obtained from Interpretive Services Branch, Nature Conservancy Council, Northminster House, Peterborough, PE1 1UA.

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A NOTE ON THE MARCH GRAVELS AND FENLAND SEA LEVELS

R.G. West*

Investigations of Late Pleistocene sequences at Somersham (TL 373794) and Block Fen (TL 428837) in the southern Fenland have demonstrated the levels of Ipswichian brackish or marine horizons. Since these sites are near the mapped spread of the marine March Gravels (B.G.S. Ely Sheet 173), it became clear that it was advisable to re-examine the March Gravels and their relation to other known recently studied brackish or marine horizons of the Late Pleistocene of the Fenland.

Figure 1 shows the locations of the sites mentioned. These brackish or marine horizons, identified by sediments with pollen assemblages and mollusc faunas, are as follows, with their heights:

Wretton, Norfolk (Sparks and West 1970)
    Ipswichian III +0.15 to +0.45m O.D.
    Ipswichian II -1.9 to -1.2m O.D.

Tattershall, Lincolnshire (Holyoak and Preece 1985)
    Ipswichian II -1.8 to -0.2m O.D.

Somersham, Cambridgeshire (West unpubl.)
    Ipswichian II -2.7 to -0.4m O.D.

Chatteris (Block Fen), Cambridgeshire (West unpubl.)
    Ipswichian III -5.5 to -6.1m O.D.
    Ipswichian II -3.7m O.D. (molluscs, pers.comm. R.C.Preece)

The occurrence and marine fauna of the March Gravels have been described by Baden-Powell (1934). He used the term March Gravel "in reference to the sands and gravels which contain marine organisms and which are found on the "islands" between Peterborough on the west and the "Bedford River", near Manea, on the east". He concluded that their heights indicated a submergence, relative to present sea-level, of 10-12m.

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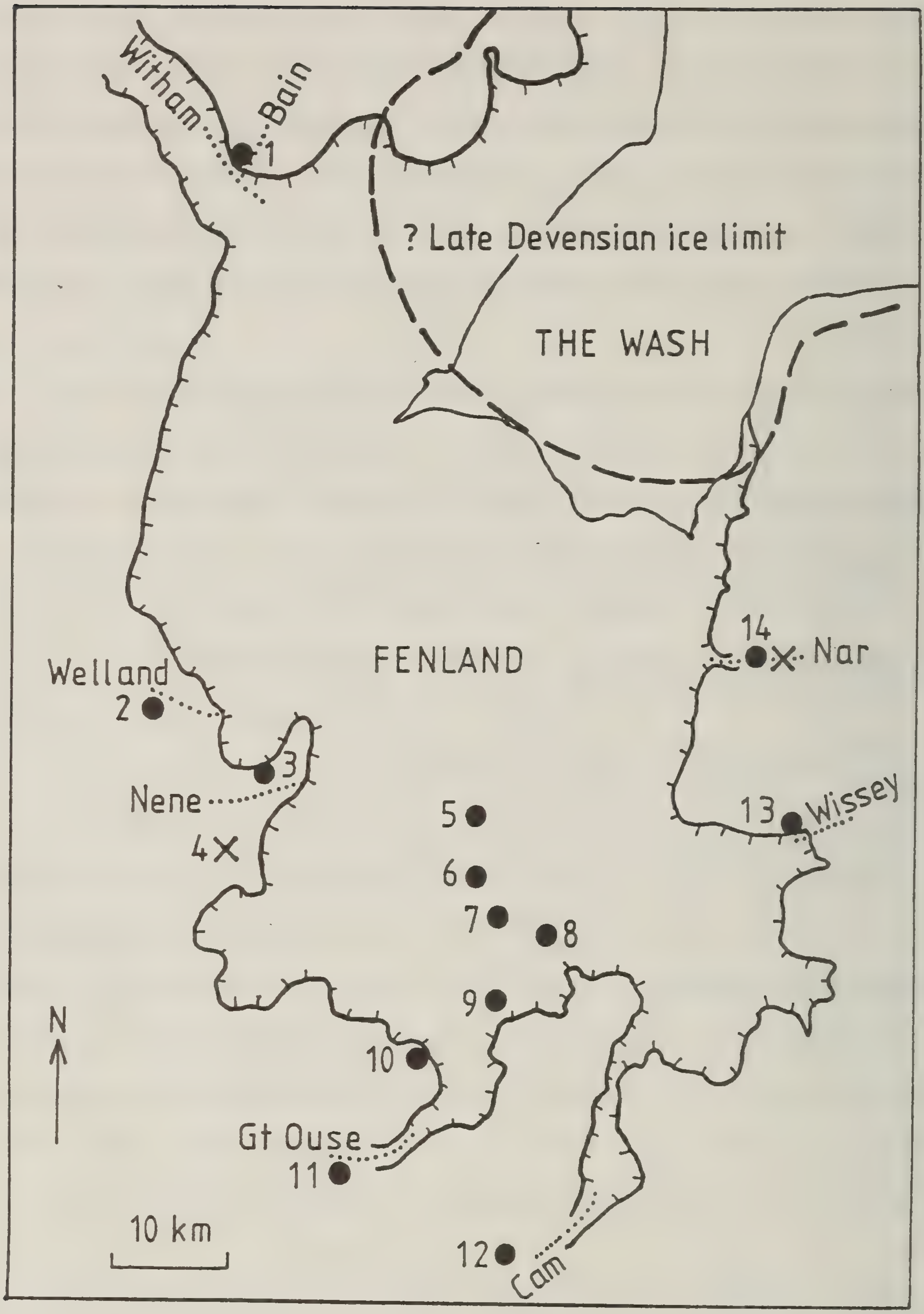
Witham
Bain
1
? Late Devensian ice limit
THE WASH
FENLAND
14
Nar
Welland
2
3
Nene
4
5
6
7
8
9
10
13
Wissey
Gt Ouse
11
12
Cam
N
10 km

March Gravels and Fenland Sea Levels

Baden-Powell's account provides a valuable list of localities for the March Gravels, with more detailed descriptions of what he regarded as the more important sections - those at Eye, Wimblington and Manea. An estimation from spot heights of the O.D. heights of the sections of fossiliferous sands and gravels at Eye and Manea indicate that at Eye they are c.3.0m to at least -2.0m O.D., and at Manea c.0.5m to at least -2.0m O.D. Levelling and boring at Wimblington proves a height of 1.0m to at least -0.5m O.D. for sands with Cerastoderma and Corbicula, and pollen analysis from mud within these sands indicates an Ipswichian age.

At March Town End sands and gravels with marine shells were proved in 1970 in a borehole at a height of 2.2m to -2.5m O.D., and were underlain by 0.5m of grey stratified silt and clay. Pollen analysis of a silt seam in the sand at c.0m O.D. indicated a late temperate age, while that of the silt and clay at the base indicated an Ipswichian II age. At Graysmoor to the north of March marine shelly sands and gravels lie at a height of -0.5m O.D.

Figure 1. Sketch map of the Fenland showing the position of certain sites mentioned in the text. The outer limit of Flandrian alluvium, peat and silt is shown. Hoxnian sites are marked by a cross, Ipswichian sites by a black circle.

Key to sites: 1. Tattershall Castle (Holyoak and Preece 1985); 2. Maxey (French 1982); 3. Eye; 4. Hicks No.2 Brickyard, Peterborough (Horton 1981); 5. Graysmoor; 6. March Town End; 7. Wimblington; 8. Manea; 9. Block Fen, Chatteris; 10. Somersham; 11. Galley Hill (Preece and Ventris 1983); 12. Histon Road, Cambridge (Sparks and West 1958); 13. Wretton (Sparks and West 1970); 14. Nar Valley (Ventris 1986).

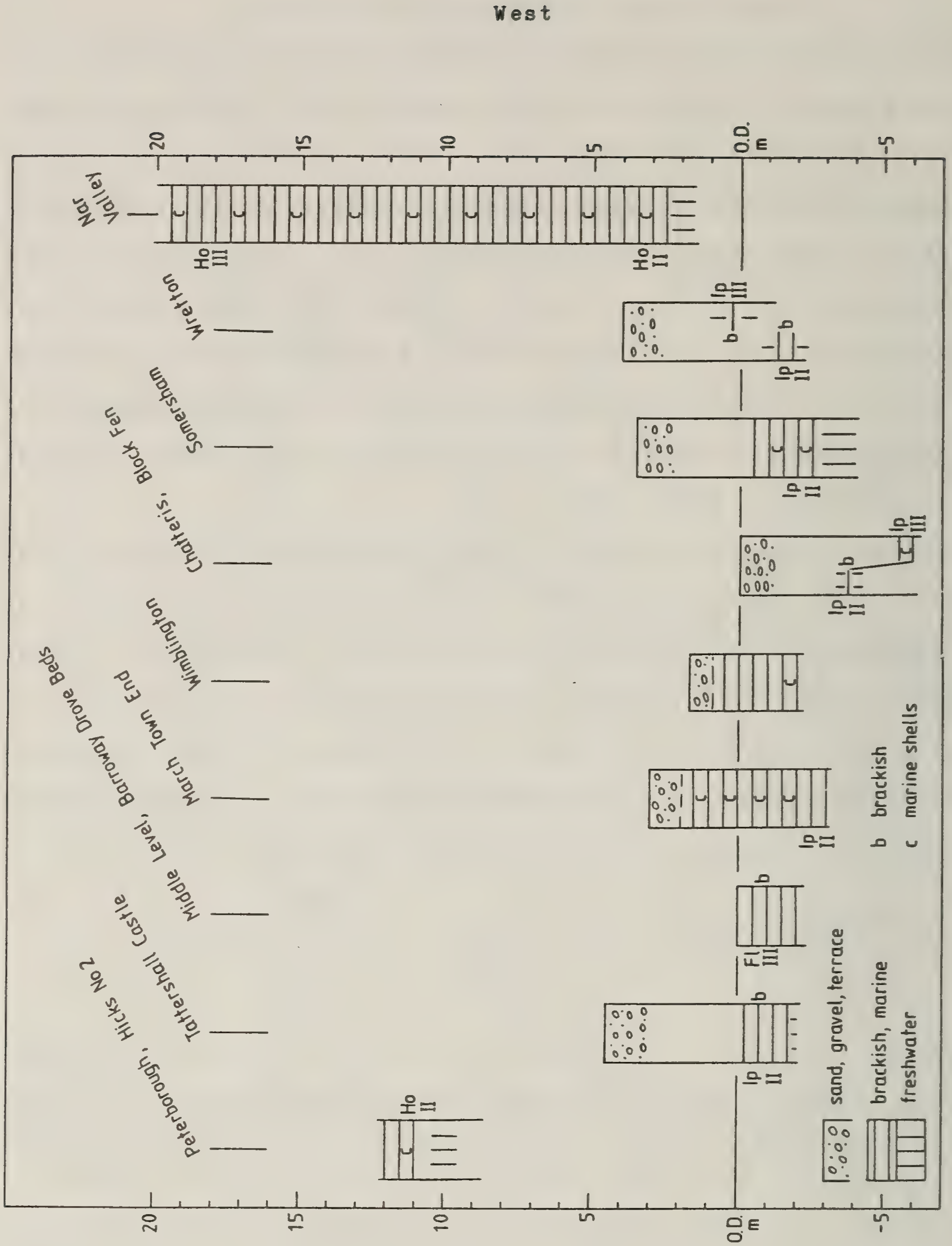
West
20
15
10
5
0.D. m
-5
Nar Valley
Ho III
Ho II
Wretton
Ip III
b
Ip II
Somersham
Chatteris, Block Fen
Wimblington
March Town End
Middle Level, Barroway Drove Beds
Fl III
Tattershall Castle
Peterborough, Hicks No 2
sand, gravel, terrace
brackish, marine
freshwater
b brackish
c marine shells

Figure 2 Levels of brackish or marine and freshwater sediments at certain sites in the Fenland. Allocations to substages determined palynologically: Ho. Hoxnian; Ip. Ipswichian; Fl. Flandrian

March Gravels and Fenland Sea Levels

The heights of sites where dating has been possible are shown in Figure 2. The evidence suggests a marine incursion into the Fenland during the Ipswichian, with sediments proved from c.3.0m to c.-6.0m O.D.

Looking at Baden-Powell's March Gravels sites as a whole, it is seen that the surface heights are variable, ranging from c.7.0m O.D. at Whittlesey, c.3.5m O.D. at March, 1.7m O.D. at Wimblington, c.2.0m O.D. at Manea, and 1.6m O.D. at Graysmoor. At Somersham the surface of the Devensian terrace above the marine horizon is 3.4m O.D. At Block Fen, Chatteris,it is c.0m O.D. At all these sites the surfaces appear to be those of terraces, underlain by gravel, sometimes capped by intervening loess-like sediment ("brickearth").

This variation in surface height of the sands and gravels (see Figure 2) strongly suggests aggradation of Devensian fluviatile sediments later than the Ipswichian marine transgression, with the eventual formation of a series of low terraces.

Since the March Gravels are mapped at the surface in extensive areas, it would seem that the term March Gravels, as at present used, may include both the Ipswichian sediments and Devensian sands and gravels. If this proves to be so, then the term should be replaced, with the Ipswichian marine sediments receiving separate stratigraphic recognition based on a type site, and with the overlying Devensian fluviatile sediments also receiving separate status. Possible type sites for the temperate marine horizon are at March Town End or Wimblington Common, both with pollen assemblages and a marine fauna, but determination of the most suitable site will have to await the completion of the present investigations. A problem of distinction between the two stratigraphic units will arise where reworked shells occur in overlying Devensian sediments.

These observations provoke a few remarks on the Quaternary history of the Fenland as a whole. In the Hoxnian, the important Nar Valley sequence on the eastern edge of the Fenland, studied by Ventris (1986), indicates that sea-level reached at least 20m O.D. in that valley, with marine clays replacing freshwater sediments at 2.5m O.D. in Ho IIc. In the Nene Valley, on the western margin of Fenland, clayey marine sediments of Hoxnian age have been described in the Woodston Beds succession of Horton (1981), e.g. in the Hicks No.2 Brickyard at heights above c.11.5m O.D. in Ho IIc. The heights of marine sediments at these two sites are shown in Figure 2. Nothing else appears to be certainly known of the Hoxnian in the Fenland basin. This is likely to indicate that there has been a radical transformation of the Fenland landscape during the Wolstonian. A study of the tills and the terraces in the area is clearly necessary to provide an account of this transformation.

In the Ipswichian, on the other hand, there are many fossiliferous sites associated with river valleys draining into the Fenland (Rivers Witham/Bain, Welland, Great Ouse, Cam, Wissey, Nar). The positions of these sites are shown in Figure 1. Their evidence indicates that the Ipswichian marine transgression into the Fenland was extensive, with, for example, sediments with _Cerastoderma_ and barnacles as far south-west as Somersham. The presence of these marine sediments must be equated with a much wider Wash in pre-Devensian times, perhaps extending north to the southern limit of the Lincolnshire Wolds, and so allowing sufficient fetch to deposit sandy marine sediments well into Fenland. Evidence for the Ipswichian sea-level does not appear to extend higher than a few metres O.D., considerably lower than the known Hoxnian levels. Evidently there was a transformation of the Fenland landscape after the Hoxnian and before the Ipswichian, with the preservation of the Nar Valley marine sediments associated with a deep pre-Hoxnian channel that only had a minor, post-Hoxnian, catchment.

In the Flandrian a totally different sedimentary environment was present, possibly resulting from the reduction of size of the Wash by deposition of Devensian glacial deposits in its mouth. In contrast to the Ipswichian sediments, the Flandrian sedimentary filling is of peat and fine-grained alluvial and brackish sediments (Figure 2). The contrast between the Ipswichian and Flandrian sequences is also likely to have been determined by different rates of rise of sea-level after the preceding cold stages and by the changing fluvial regimes of the principal fenland rivers.

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CONTENTS

		Page
Editorial		1
Goff, J.C.	The Formation of the Giant Oil Fields of the Northern North Sea (Presidential Address for 1986)	3
Duff, K.L.	Geological Conservation in Britain	19
West, R.G.	A note on the March Gravels and Fenland sea levels	27

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The illustration on the front cover is taken from Figure 286 of Lyell's "Elements of Geology", 1865 (6th Edition), and shows columns of potstones in the Late Campanian Chalk of a quarry on the River Bure near Horstead, Norfolk. The upper part of the section consists of Crag gravels resting on an erosion surface which truncates the potstone columns.

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